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Addressing the Issue of Microplastics in the Wake of the Microbead-Free Waters Act—A New Standard Can Facilitate Improved Policy

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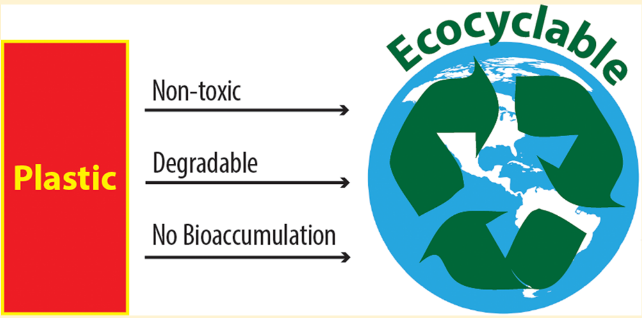
Supporting Information

ABSTRACT: The United States Microbead-Free Waters Act was signed into law in December 2015. It is a bipartisan agreement that will eliminate one preventable source of microplastic pollution in the United States. Still, the bill is criticized for being too limited in scope, and also for discouraging the development of biodegradable alternatives that ultimately are needed to solve the bigger issue of plastics in the environment. Due to a lack of an acknowledged, appropriate standard for environmentally safe microplastics, the bill banned all plastic microbeads in selected cosmetic products. Here, we review the history of the legislation and how it relates to the issue of microplastic pollution in general, and we suggest a framework for a standard (which we call "Ecocyclable") that includes relative requirements related to toxicity, bioaccumulation, and degradation/assimilation into the natural carbon cycle. We suggest that such a standard will facilitate future regulation and legislation to reduce pollution while also encouraging innovation of sustainable technologies.



INTRODUCTION

Plastics have become an indispensable material in modern society. Due to increased production and imperfect waste management, the accumulation of discarded plastics in the environment is escalating. Much of this plastic litter exists as small particles (microplastics, defined as <5 mm in size).[1] Until recently, these microplastics were overlooked, but they are now recognized as a major environmental pollutant of concern. This concern was manifested in the United States Microbead-Free Waters Act of 2015 (hereafter referred to as the "Act"), which bans the use of small (<5 mm in size), intentionally manufactured plastic particles (a.k.a. microbeads) in rinse-off personal care products. These microbeads are used as abrasive scrubbers in products such as facewash, body wash, and toothpaste. The Act, which passed with overwhelming bipartisan support, was signed into law on December 28, 2015.

The Act will reduce microplastic pollution, and thus is a step forward. Still, it receives criticism for two main reasons. First, it only reduces *one* of *many* sources of microplastics that we find in the environment. The Act does not cover microbeads added to certain types of cosmetics (e.g., makeup to reduce wrinkle lines), nor does it include secondary microplastics (e.g., microplastics produced by fragmentation of larger plastics such as those produced by washing of fabrics or weathering of larger plastic products), which make up the large majority of microplastics found in the environment.[2] Thus, microbeads are a relatively small source of microplastic litter.[2] Second, the Act is criticized for treating all plastics the same, even innovative bioplastics with limited environmental impact. Consistent with the typical legislative process, the language of the Act was a compromise between concerned parties. As described below, semantic issues and the lack of an efficient, multidimensional standard prevented reaching a compromise that would have provided broader and better public policy. The proverbial pie was split, but in a manner that left pieces on the table.

Ideally, we can learn from this particular legislative process in order to facilitate future efforts that address the broader plastic problem. In particular, the lack of an appropriate standard for environmentally safe materials, encompassing not only biodegradation but toxicity (including of additives) and bioaccumulation, indirectly led to language in the Act that banned *all* plastic microbeads from rinse-off personal care products.

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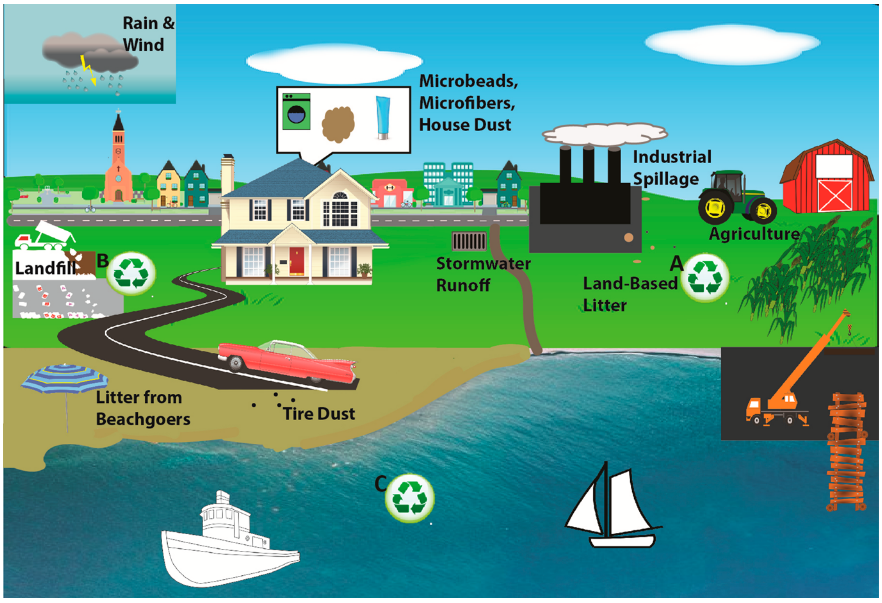

Figure 1. Sources and fate of plastic debris. Many different sources of plastic debris, as well as environments in which they wind up, are depicted in this image. Letters refer to the three types of environments that were chosen for the Ecocyclable standard: (A) aerobic soil; (B) anaerobic methanogenic environment (as found in modern landfills and anaerobic digesters at wastewater treatment facilities), and (C) aquatic environment.

Given the larger problem of plastic debris in the environment, and in many cases the deficiencies of potential alternatives (including cost, performance, and/or environmental impact) to the roughly 300 million metric tons of plastics produced annually worldwide,[3] we believe that a patchwork collection of bans on plastics in various applications is not the best way forward. Instead, development of sustainable plastics that are environmentally safe (or at least reasonably so, recognizing that no material, even pure water, is safe everywhere for all species in all embodiments) should be encouraged, while environmentally harmful materials (including additives) should be discouraged.

Accordingly, we introduce a new standard that we term "Ecocyclable", which aims to inform future legislation and product development. Ideally, such a standard would be broad in scope, reflect the most informed scientific consensus, and require only inexpensive, short-term testing to ensure compliance. Herein we propose an initial standard (Ecocyclable 1.0) which hopefully can be improved through an iterative process.

Plastics, Microplastics, and Microbeads. Plastic debris presents a global management challenge. At their end-of-life, plastics enter the waste management system where they are recycled, incinerated, or sent to a landfill or dump.[4] Plastics that are littered do not enter waste management systems, and can be readily transported by wind and ocean currents across international borders and oceans. A recent report calculated that the introduction of plastic into our oceans is increasing at an alarming rate, with 4.8−12.7 million metric tons of mismanaged plastic waste entering in 2010 and 10 times that amount projected by 2025.[3]

When plastics enter the oceans, they slowly break into ever smaller fragments of microplastics via physical degradation, photodegradation, and biodegradation. While physical degradation can be quick, the biodegradation process can take centuries.[5] Microplastics have been reported on the surface of every major open ocean,[1,6] in the deep oceans,[7] and in freshwater lakes and rivers.[8,9] Microplastics have even been reported in Arctic sea ice[10] and atmospheric fallout.[11] This small plastic becomes litter in the aquatic environment from a number of diverse sources,[2] including primary sources such as plastic microbeads in cosmetics, industrial abrasives and accidental preproduction pellet spills from industry, but also many secondary sources such as tire dust from vehicles, fragments of agricultural plastics, microfibers from textiles, and littered plastic items that degrade over time into smaller and smaller pieces (see Figure 1). Secondary microplastics are thought to be the most common type of microplastics in the ocean.[2]

As mentioned above, microbeads are one type of microplastic. They are designed and manufactured as they are found (i.e., primary microplastics). In the context of the Act, plastic microbeads are defined as synthetic polymers, typically between 10 and 500 μm (for comparison, the diameter of a human hair is roughly 80 μm), which are used in rinse-off personal care products to exfoliate or cleanse. Microbeads are often made out of polyethylene, polylactic acid, polypropylene, or polystyrene.[12] The microbead-containing products are applied to the body, then rinsed off and washed down the drain into a wastewater stream. Where there is wastewater treatment, microbeads will flow to the treatment facility; where there is not, they will flow directly into our watersheds.[13] During the treatment process, a small fraction of microbeads remains in the final effluent and is released to rivers, lakes, and oceans. The rest are entrained in biosolids (sewage sludge).[13] Land-application of biosolids reintroduces microbeads to the terrestrial environment, with the potential to enter aquatic habitats via runoff following a storm or irrigation. Once in the environment, they are available to wildlife and have been found in the gut content of fish.[14]

Adverse impacts of microplastics to animals are a concern, particularly given the global contamination of habitats and organisms.[15] Microplastics have been reported in over 100 species of wildlife across all trophic levels,[15] including in shellfish,[16] and fish[17] sold for human consumption. Both microplastics and associated chemicals can bioaccumulate in animals.[18,19]

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In experiments, impacts from exposure to microplastics have been demonstrated at molecular, cellular, population, and community levels,[20] including reduced reproduction in copepods[21] and oysters[22] and altered species richness in an invertebrate community.[23]

The Act. To begin, why did legislation focus on microbeads? If we look at proposed solutions to prevent plastic debris, frequently they involve a ban or imposed fee on single-use plastic items. For example, California recently became the first state to ban single-use plastic bags (Proposition 67). Such bans do not typically come easily and can be controversial. Relative to other single-use items, microbeads were a legislative low-hanging fruit. The societal benefit of plastic microbeads in rinse-off personal care products is not compelling, and the waste management stategy for microbeads assures they will end up in the environment. Moreover, drop-in replacements (e.g., ceramic microbeads or crushed walnut shells) are readily available in the market and would have only a modest impact on profit margins. Thus, a ban on microbeads seemed a good first step that was less likely to face determined opposition.

The process that led to the U.S. legislation began with organizations from across the globe working together and engaging with industry. In the U.S., the nonprofit organizations 5 Gyres Institute and Story of Stuff Project led a campaign to (i) educate the public about microbeads, (ii) pressure manufacturers to remove microbeads from their products, and (iii) work with legislators to ban microbeads. The campaign was successful. Major companies (e.g., Proctor & Gamble and Unilever) agreed to phase out plastic microbeads from certain products even before legislation was passed.

Legislation was first targeted at the state level, recognizing that piecemeal legislation in multiple states and smaller jurisdictions would force Federal legislation by creating logistical and distribution problems for companies. Rather than formulate different products for different jurisdictions, manufacturers would be compelled to create a single product that complied with the most stringent legislation.

In 2014, Illinois became the first state to pass legislation on microbeads. However, this bill fell short of the goals of most environmental groups. The definitional fine print was critical. The Illinois legislation defined synthetic plastic microbeads as "any intentionally added non-biodegradable solid plastic particle". The bill excluded biodegradable plastics, but did not define that term, creating a loophole. One could argue that a material is "biodegradable" even though it degrades only marginally over several years, for example, modestly changing in shape and form, but persisting in the environment.[24] Thus, any legislation that fails to define "biodegradable" (or alternatively cites standards for biodegradability that do not mandate full degradation, especially in aquatic environments) allows for materials to be used that degrade only slightly during a given period of time.

The definition of "plastic" was also problematic. Plastic was defined as "a synthetic material made from linking monomers through a chemical reaction to create an organic polymer chain that can be molded or extruded at high heat into various solid forms retaining their defined shapes during life cycle and after disposal" (Illinois Bill SB2727). First, not all polymers are made by linking monomers. Additionally, some plastics are made by modifying existing polymers. For example, cellulose acetate (which in some forms can be biodegradable) is made by acetylating the natural polymer cellulose, rather than by linking monomers. Second, this definition would not cover plastics that melt at low temperatures. Finally, it might not cover certain plastics depending on the design of the final product; for example, one could even argue that an ordinary polyethylene plastic milk jug (which requires only minimal force applied to the thin side walls before losing its shape) would not meet this definition of "plastic".

Environmental groups felt that the letter of the Illinois law did not match the spirit of the law.[25] As a result, when proposing legislation in California, the groups aggressively pushed for wording to eliminate loopholes with respect to biodegradability. Extensive discussions were held between the personal care product representatives, policy-makers, academic scientists, and environmentalists, but all parties could not agree upon a definition of biodegradability, which led to the deletion of that term from the bill altogether. As a consequence, the California bill banned microbeads made from any plastic, with no exceptions. However, all groups agreed that new legislation would only apply to "rinse-off products". Thus, the legislation excludes items such as makeup, lotions, deodorant and industrial and household cleaners. Legislation that passed in other states had language that was modeled upon either the Illinois bill (i.e., full of loopholes), or the California bill (i.e., all plastics banned, irrespective of their environmental impact). Ultimately, the Federal Act mirrored the California legislation.

Of course, the Federal "Microbead-Free Waters Act" does not eliminate all microbeads from aquatic habitats, let alone all microplastics. It is estimated to eliminate only a small fraction, between 0.1% and 4.1%,[26] of the microplastics that enter aquatic habitats. Although many other sources of microplastics exist, including some that may be more prevalent (e.g., microfibers from textiles),[27] the Act focuses on just one source: microbeads in rinse-off personal care products. Still, although cosmetic microbeads may be only a small fraction of microplastic pollution, they are not inconsequential: a recent calculation estimates the Act may prevent >2.9 trillion pieces of microplastic from entering waterbodies per year.[13]

Overall, the Act was well-intentioned and provides tangible benefits, but improved language would have yielded a bill that is both more effective public policy and viewed more favorably by people on all sides of the issue. For example, some environmentalists argue the Act is too limited in scope and does not do enough to solve the microplastics issue, some scientists argue it puts too much attention on a contaminant (i.e., plastic microbeads) whose hazards are less well-understood than others (e.g., pesticides), and some industry groups argue that the prohibition of all plastic microbeads stunts innovation. Unquestionably, the lack of standards and scientific consensus defining biodegradation of plastics contributed to the imperfect final language in the Act.

Due to the magnitude of the contamination of microplastics, complete removal via clean-up is not possible. The most effective solutions are those that eliminate microplastics at the source. Bans on non-biodegradable plastic tableware (e.g., in France),[28] single-use grocery bags (e.g., in California),[29] and packaging (e.g., in Nantucket, Massachusetts)[30,31] have been passed recently in various jurisdictions, and similar laws are likely to be proposed in jurisdictions around the globe. In crafting future legislation, it will be difficult for policymakers to choose legal language that satisfies all concerned parties and also provides effective public policy. Accordingly, we propose a solution to the standards/definitional problem, and hope that it helps avoid future scenarios in which nuanced or clumsy legal language either: (i) prevents legislation altogether, (ii) creates

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Environ. Sci. Technol. 2017, 51, 6611−6617

loopholes that permit environmentally unfavorable activities contrary to the intent of the legislation, or (iii) bans entire classes of materials that might be environmentally sound and cost-effective.

Ecocyclable Standard. Future regulatory or legislative policy would be easier to write if there was a scientifically informed standard that clearly distinguished between environmentally friendly plastic compositions and those that are persistent, bioaccumulative, and/or toxic. This would help avoid the definitional and semantic issues that plagued the microbead legislative efforts.

Biodegradation (i.e., degradation mediated by microorganisms) is a term that is widely used to suggest environmental acceptability. In putative future legislation, one might argue in support of an exception for "biodegradable" plastics, and there are dozens of published tests/assays for biodegradation.[32] Should not it be easy to craft suitable language? Not exactly. Biodegradation is desired, but in what time frame? And to what extent, if 90% of a composition degrades, is that sufficient? And in which environments? Biodegradation is generally more easily achieved in a warm, moist, compost heap than in dark, cold, high-salinity water. Moreover, just because a plastic biodegrades does not ensure that it is environmentally benign. It could degrade to toxic monomers, or leave behind toxic additives such as plasticizers or stabilizers. Other degradation processes, such as photodegradation, chemical degradation, and physical degradation, can also have important roles. Ultimately, a standard for environmentally benign materials should require that the materials degrade into products that are readily incorporated into the natural carbon cycle, are nontoxic, and do not lead to the accumulation of persistent additives in food chains.

However, given the wide scope of variables such as plastic compositions, processing aids, processing parameters, degradation routes, impacted organisms, and microenvironments, crafting such a standard is difficult. Just as degradation cannot be assessed for every possible environment, toxicity cannot be assessed for every possible organism, and bioaccumulation cannot be assessed for every possible food chain. These considerations make it difficult to define a standard for environmentally safe materials, even for a diverse, scientifically trained panel with no time constraints or pressure from lobbyists or attorneys on either side of an issue. However, given the importance of public policy initiatives regarding plastic waste, it seems imprudent to leave this task to overburdened legislators and expect them to arrive at an appropriate standard.

To guide and facilitate future policy-making efforts, the scientific community should put in place a standard that defines the essential characteristics of environmentally benign materials. Given that there are no perfect and universal assays of degradation or toxicity, a balance must be struck between society's need for new and useful materials, and requirements for efficient testing (measured in time and cost) to determine environmental safety.

In an effort to address this challenge, we propose and define a new term: "Ecocyclable" (see Box 1 and note that the complete text of the definitional footnotes can be found at www.ecocyclable.org). This standard covers the extent and rate of degradability, along with the end products of degradation (both their toxicity and ability for assimilation in the carbon cycle). We wanted to use a term that was: (i) not already widely used to describe commercial products (e.g., "ecosafe"), and (ii) suggestive that a material could be naturally and safely recycled into the carbon cycle without any human intervention.

Box 1

A material, including its additives, is ***Ecocyclable*** in a given environment[a] if it satisfies the following criteria for degradability, bioaccumulation, and toxicity:

(1) In a 180-day period[b] in said environment, representative samples (between 100 mg and 25 g, depending on the particular test) of the material degrade[c] to an extent at least 25% of that observed in an equivalent mass of the reference sample, wherein said reference sample has equivalent (or greater) surface area relative to the material sample, and is comprised of either cotton fiber[d] or poly-3-hydroxybutyrate[e]; AND

Within a period of between 180 days and 18 months in said environment, representative samples (between 100 mg and 25 g, depending on the particular test) of the material degrade[c] to an extent at least 90% of that observed in an equivalent mass of the reference sample;

(2) The material and associated additives do not bioaccumulate[f] in representative organisms; and

(3) The material and/or its additives have toxicity[g] that is not significantly (as determined by rigorous statistical testing, $\alpha = 0.05$) greater than that of a comparable composition (size and shape) of either cotton fiber[d] or poly-3-hydroxybutyrate[e] under acute and chronic exposures to environmentally relevant concentrations.

For this standard, it is not possible to test degradation in all conceivable environments, or to assess toxicity or bioaccumulation in all relevant species. Instead, we have selected three representative environmental conditions for which a material can qualify as Ecocyclable. These include (a) aerobic soils; (b) anaerobic methanogenic environments (as found in modern landfills and anaerobic digesters at wastewater treatment facilities); and (c) aquatic environments (e.g., pelagic, benthic sediments, or estuarine). These environmental conditions are locations where many plastics ultimately end up,[3,13] and the specific tests selected are representative of favorable real-world conditions, designed to test if a material is intrinsically inert and therefore resistant to entry into the natural carbon cycle.

To address issues of toxicity and bioaccumulation, we limit the number of test organisms to those that are already used as standardized test species, and we include standard toxicology assays wherein the test conditions are relevant to the materials and the environment, including considerations of size and toxicity of leachate.

While it is tempting to define absolute requirements for degradability and toxicity (e.g., "no known toxicity in a representative species"), such a standard would disqualify many natural materials that are reasonably safe. For example, cotton can be hazardous if individuals are exposed to sufficient quantities of cotton dust (leading to brown lung disease).[33]. Thus, a prohibition on any product that can be hazardous to health would exclude materials that are almost universally considered environmentally acceptable. Instead, we propose a relative standard based on two naturally occurring materials that are ubiquitously distributed around the planet, are not typically toxic, and biodegrade (at varying rates) in most environments.[34,35] The proposed reference materials are (i) cellulose, an ether-linked organic polymer that is a natural

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Environ. Sci. Technol. 2017, 51, 6611−6617

structural component of plants; and (ii) poly-3-hydroxybutyrate (PHB), an ester-linked organic polymer that is a natural energy storage material in microorganisms. Cellulose is the main component of natural fibers such as cotton, jute, hemp, and linen; thus, we have selected cotton fiber (which consists primarily of cellulose) as a reference material for synthetic textile fibers (e.g., acrylic and polyester fibers, which are shed in washing machine cycles and are significant source of microplastic pollution).[36] Meanwhile, PHB, a natural thermoplastic, serves as a reference material for moldable polymers. This ensures that a test material can be compared to a reference material having comparable physical characteristics and surface area. Note that cellulose and PHB are already used as reference standards in tests for biodegradation (e.g., ISO 17556). Molecular weight impacts the rate of degradation, so we have defined reference standards having a molecular weight of 1000 000 Da, which is near the high end of the natural molecular weight ranges for PHB[37] and cotton.[38]

For a material to qualify as Ecocyclable under this framework, it needs to degrade, as measured by standard test methods, within two specified time periods, at no less than a specified percentage of the degradation of the appropriate reference standard. We have included a six-month rate component and an 18-month comprehensive degradation component (which is required to minimize false positives from the rate component of the test) in our definition. While rapidly degrading materials can qualify quickly, other materials could require all of the allotted 18 months to meet the ultimate degradation standard (minimizing false negatives that could occur with shorter testing). We recognize that long test periods associated with the comprehensive degradation test can be problematic; however, without a comprehensive degradation test, shorter tests that require only a modest percentage degradation can easily lead to passing grades for materials that have a component that is resistant to degradation (provided it is combined with a sufficient quantity of a material that degrades quickly).

Any material that passes the degradability test in all three test environments and also passes tests for toxicity and bioaccumulation would be "Generally Ecocyclable". Materials that meet the standard in at least one environment (e.g., aerobic soil/wastewater), but not all environments, would be "Conditionally Ecocyclable". This Ecocyclable standard can also include (and distinguish) starting materials and end products (although it does not address the issue of feedstocks and their origin or sustainability). For example, a particular grade of polymer could be Ecocyclable, but that does not mean all products made with that polymer would be Ecocyclable; instead, it would depend on the composition of additives. We suggest sufficient replication in testing to establish that the Ecocyclable criteria are met with a high degree of confidence (e.g., $p < 0.05$ for each criterion). The definition and more information about this framework can be found on the Ecocyclable Web site.

This definition is intended to distinguish between materials that are environmentally benign and those that are not. There is significant challenge in both preventing false positives and avoiding false negatives. However, the ramifications of not changing our current trajectory with respect to the release of plastics to the environment and their impact on the planet's ecosystem are unacceptable. Improvements to this initial definition of Ecocyclable might become apparent over time, and iterative refinements based on input from a broad array of stakeholders may be needed (analogous to open source software licenses; e.g., GPL-2.0, GPL-3.0, etc.[39]).

Our goal is to produce a scientifically informed standard that policy-makers can use as a reference when creating legislation that rejects nonsustainable and hazardous products, and/or incentivizes innovation of products that are truly sustainable and safe. For example, recently proposed legislation in California (Assembly Bill 1594) calls for a study and subsequent recommendations regarding "legislative action or other strategies that may be implemented by the state to reduce plastic pollution on state beaches and in oceanwaters", and notes that "non-biodegradable plastic litter poses a real and growing threat to water quality and the marine environment". Instead of attempting to translate these goals into legislation by (i) obtaining expert scientific knowledge to determine whether or not photodegradable compositions were acceptable, (ii) trying to define the term "biodegradable", (iii) trying to identify and then exclude certain additives in a biodegradable plastic that might be toxic, and (iv) trying to identify potential loopholes in a highly technical redlined document, legislators could instead consider specific applications (e.g., disposable cutlery or single-use packaging) and simply choose to ban nothing (as would be the case with no legislation), or ban or incentivize materials based on whether they met the standards for being Conditionally Ecocyclable and/or Generally Ecocyclable The result is legislation that may be easier to pass and more likely to result in the letter of the law matching the spirit of the law.

For example, many formulations of the biopolymer polylactic acid (PLA) are not Generally Ecocyclable (e.g., because of insufficient marine degradation), but are Conditionally Ecocyclable. Industrially compostable PLA cups are widely used. Irrespective of best waste management practices, some of that PLA ends up in marine environments. Nevertheless, the use of the Conditionally Ecocyclable plastic PLA might be preferable to conventional plastic in some scenarios (at least in the absence of cost-effective alternatives that are Generally Ecocyclable), and legislators could choose to distinguish PLA or other Conditionally Ecocyclable plastics from conventional plastics. By incorporating incentives for Generally Ecocyclable products, or phasing out other products, legislation could promote the development and use of plastics that are more environmentally preferable.

Implementation of this standard could take multiple forms, the two most obvious of which have as a downside either high uncertainty or high cost. The high-cost approach requires testing and/or certification. For example, an existing organization such as ASTM or Vincotte could be entrusted with providing official certification. Similarly, a government agency or a nonprofit group could be specifically tasked with this agenda. Nevertheless, irrespective of who is responsible for testing and certification, there would be significant costs. Another alternative (i.e., the high-uncertainty, low-cost approach) is simply to have a defined standard without any necessary certifications. Legislation would require that an Ecocyclable standard be met, and manufacturers would have the responsibility to ensure that their own products complied with the law. Obviously, some companies might falsely advertise a product as Ecocyclable, and/or sell products using materials banned for that application. However, these companies would then be subject to legal and market-based ramifications. Our inclination is to recommend the low-cost approach, at least at the outset and hopefully in perpetuity.

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CONCLUSION AND OUTLOOK

Waste management is generally managed locally, but microplastic debris has global implications.

Microbeads brought microplastics to the attention of many people who were previously unaware of this issue. The rapid passage of the Microbead-Free Waters Act marked a landmark moment in efforts to mitigate this burgeoning global concern. As public policy solutions to other components of the microplastic problem are being proposed around the world, we hope that a scientifically vetted standard will inform policy-making such that future efforts to address microplastic pollution will (i) mitigate a larger proportion of the microplastics issue, and (ii) allow innovation of products that are relatively safe for the environment. Recognizing both the difficulty of crafting suitable language, as well as the benefits of incorporating new scientific knowledge into testing methods, we hope that the scientific community can help to iteratively improve the standard we have proposed for Ecocyclable materials.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b05812.

Additional information as noted in the text (PDF)

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Notes

The authors declare the following competing financial interest(s): The authors don't believe there is any competing financial interest, but note that Molly Morse is CEO of Mango Materials, a company trying to develop large-scale production of PHA from waste gas.

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Dr. Molly Morse is the CEO and cofounder of Mango Materials, a San Francisco Bay Area-based start-up company that uses methane gas to feed bacteria that manufacture a naturally occurring biopolymer. She is currently working to scale the manufacturing technology to produce environmentally friendly materials.

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