Minimizing the environmental impacts of plastic through eco-design

Bryan D. James[1,2,], Collin P. Ward[1], Mark E. Hahn[2], Steven J. Thorpe[3], Christopher M. Reddy[1]*

[1]Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution; Woods Hole, MA 02543, USA.

[2]Department of Biology, Woods Hole Oceanographic Institution; Woods Hole, MA 02543, USA.

[3]Department of Materials Science and Engineering, University of Toronto; Toronto, Ontario M5S 3E4, Canada.

*Corresponding author. Email: bjames@whoi.edu

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ABSTRACT

While plastic pollution threatens ecosystems and human health, the use of plastic products continues to increase. Limiting its harm requires strategies when designing plastic products informed by the threats plastics pose to the environment. Thus, we developed a sustainability metric for the eco-design of plastic products with low environmental persistence and uncompromised performance. To do this, we integrated the environmental degradation rate of plastic into established material selection strategies, deriving material indices for environmental persistence. By comparing indices for the environmental impact of on-the-market plastics and proposed alternatives, we show that accounting for environmental persistence in design could translate to societal benefits of hundreds of millions of dollars for an individual consumer product. Our analysis identifies which materials deserve adoption and investment to create functional and less environmentally impactful products.

SYNOPSIS

We propose a novel sustainability metric for selecting materials in product design that minimizes plastic pollution.

INTRODUCTION

Sustainability and the circular economy have become cornerstones of corporate strategy.[1,2] Today's products must satisfy the needs of engineering, marketing, business, regulation, and consumer preference while also being sustainable.[3] Design decisions rely on eco-design and green chemistry principles, life cycle assessments (LCA), and related methods to reduce a product's environmental impact.[4-10] Plastics and their pollution challenge current approaches in the design of sustainable products. Materials are selected principally by balancing tradeoffs between environmental impact categories, such as greenhouse gas (GHG) emissions and water usage during production. However, environmental persistence, defined as the time a plastic item lasts in the environment as pollution, is missing from the selection criteria (e.g., in LCA[11,12]).

While plastics do break down in the environment,[13-19] estimates of the environmental lifetimes of plastic products have only recently been made. These estimates vary widely and range from months to decades or longer.[20] Biotic and abiotic processes act to fragment, degrade, transform, modify, assimilate, and mineralize plastics.[13,21,22] The efficiency and selectivity of these processes depend on environmental conditions, the type of plastic, and the functionality and geometry of the product,[13] i.e., on features of product design. Thus, an opportunity exists to consider environmental breakdown in the design of plastic products. Because some plastic products will inevitably enter the environment as pollution, regardless of waste management strategies, it is necessary to confront their persistence.[23]

With the understanding that more persistent materials pose greater potential threats to ecosystems and human health, environmental persistence is a fundamental principle of regulatory frameworks.[24] Therefore, considering persistence during product design by selecting materials that quickly break down when leaked into the environment presents an opportunity to minimize risks to ecosystems and human health. Recently collected data on environmentally realistic plastic degradation rates catalyze this thinking. Here, we aggregate concepts learned from the past decades of plastic pollution research and integrate them into established material selection practices, formulating a novel eco-design framework for minimizing the environmental impacts of plastic pollution.

RESULTS & DISCUSSION

Selecting appropriate materials is critical for engineers,[25] industrial designers,[26] and architects[27] to create functional and aesthetically pleasing products. According to Ashby,[28] the problem of choosing the "best" material can be framed as a collection of design requirements (i.e., functions, objectives, and constraints) for which material indices (MIs) can be determined and optimized. MIs are material properties or groups of properties that maximize performance for a given objective (e.g., minimizing mass, cost, or an environmental impact).[25]

A Material Index for Persistence.

Missing from material selection is an MI for environmental persistence, i.e., a metric for optimizing the environmental lifetime of an item after its release to the environment as pollution. Degradation rates are material properties and thus can be included as an integral part of product design. While definitions for degradation can vary,[13] herein, we limit the definition of degradation to overall mass loss from the initial plastic item in marine environments.

Complementary to this, we define environmental lifetime as the time it takes for an item's mass to reduce to zero because of degradative processes. Accordingly, we propose that persistence can be included in material selection by considering the design objective to minimize environmental lifetime at end-of-use. Much like other MIs (**Table S1**, **Section S1**), we developed an approach to derive MIs for environmental lifetime by i) defining the appropriate objective equation and ii) substituting relationships for the initial geometry of the item specified by the design constraints.

To demonstrate the approach, consider the design of a stiff beam (**Figure 1A**). A typical function for a beam is to support a load without sagging. Rather than minimize the beam's mass or cost, the design objective for persistence is to minimize the beam's environmental lifetime at end-of-use. The design constraints on the beam define the loading conditions, amount of tolerable deflection, and geometry. The free, unconstrained variables are the choice of material and some geometric features. To derive an MI for persistence, we first defined the objective equation by solving a degradation rate equation, establishing a mathematical relationship between environmental lifetime and the geometry of the beam.

The uniform degradation rate of a plastic item in the environment can be defined as the differential mass loss per unit time ($\frac{dm}{dt}$), equal to the product of the surface area (A_s) of the item and the density (ρ) and specific surface degradation rate (k_d) of the item's material (**Equation 1**).[13]

$$\frac{dm}{dt} = -\rho k_d A_s \quad (1)$$

In this formulation, k_d is a phenomenological parameter that assumes all mass loss is by surface erosion. Notably, this framing implies that intrinsic properties of the material and extrinsic properties of the item (e.g., shape, size) control the item's degradation rate.

Additionally, k_d is a coupled material-environment property that condenses the effects of plastic formulation and processing, and environmental conditions into a single term (i.e., values of k_d in seawater and soil are different).

Assuming a solid beam with a square cross-section, we solved **Equation 1** (see supplementary text, section 2 for derivation) to yield a relationship between environmental lifetime (t_L), the initial edge length of the cross-section (b_0), and k_d (**Equation 2**).

$$t_L = \frac{b_0}{2k_d} \tag{2}$$

Thus, minimizing t_L requires minimizing b_0 and maximizing k_d. However, this relationship is incomplete. The predefined design constraints dictate b_0. From beam theory (**Section S2**), b_0 can be defined in terms of the tolerable deflection (δ) of the beam, the beam's initial length (l_0), the supported load (F), the loading and support configuration (C_1), and the Young's modulus (E) of the beam's material (a measure of a material's resistance to elastic deformation) (**Equation 3**).

$$b_0 = \left(\frac{12F{l_0}^3}{C_1 E \delta}\right)^{\frac{1}{4}} \tag{3}$$

Substituting **Equation 3** into **Equation 2** relates the environmental lifetime in terms of the design constraints (**Equation 4**). For more complex items, numerical methods (e.g., finite element simulations) can be used to solve **Equation 2** for determining relationships between environmental lifetime and material properties, as done for other MIs.[29]

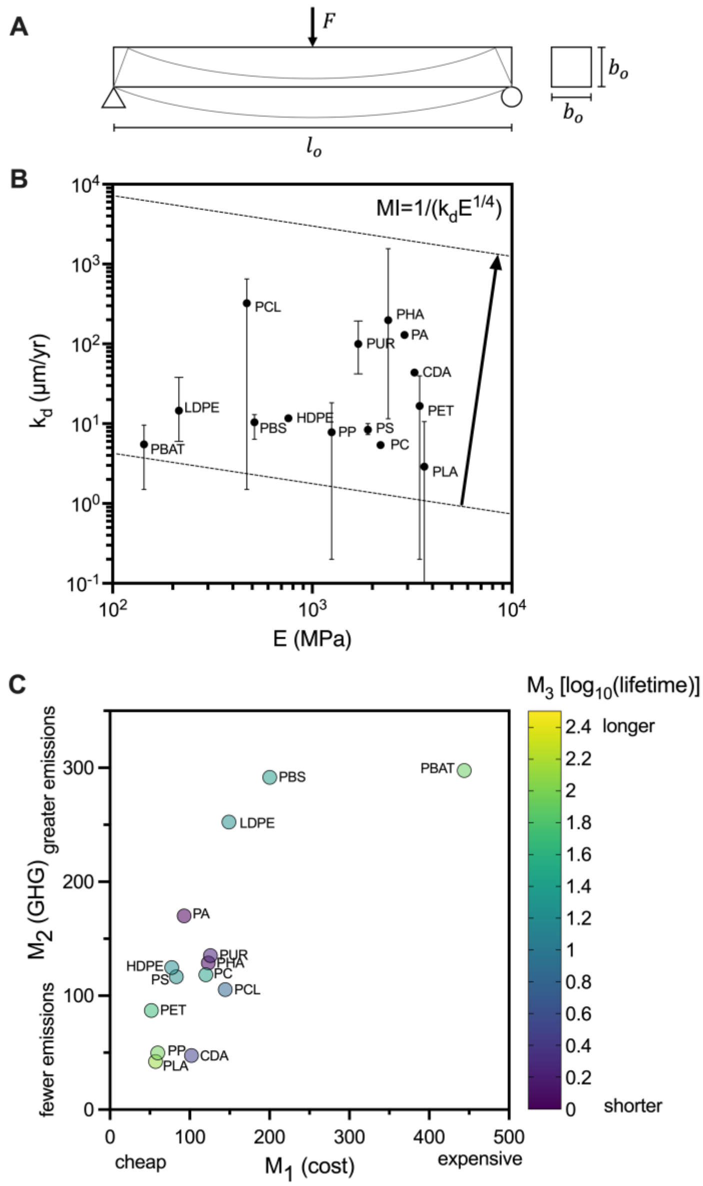
$$t_L = \left(\frac{12F}{C_1\delta}\right)^{\frac{1}{4}} \left(\frac{l_0}{\sqrt[3]{16}}\right)^{\frac{3}{4}} \left(\frac{1}{k_d E^{\frac{1}{4}}}\right) \tag{4}$$

Grouping the terms for material properties expressed in **Equation 4**, the MI for minimizing the persistence of a beam with a solid square cross-section is $\frac{1}{k_d E^{1/4}}$. Notably, this MI implies that minimizing the beam's environmental lifetime requires considering a material's k_d and E. Using reported values for k_d and E of several plastics, functionally equivalent beams made from polycaprolactone (PCL) and polyhydroxyalkanoates (PHA) could be the least persistent, followed by cellulose diacetate (CDA), polyamide (PA), and polyurethane (PUR) (**Figure 1B**). Conversely, functionally-equivalent beams made from commodity polyolefins and several compostable polyesters would be expected to persist much longer.

Tradeoffs: Considering the Cost of Pollution.

In practice, products cannot solely be designed to minimize persistence at end-of-life; products must satisfy multiple, often competing, design objectives. Using literature data for several plastics, we calculated MIs to optimize a beam with a solid square cross-section in terms of financial (cost) and sustainability metrics (embodied GHG emissions and environmental lifetime). The choice of material had much greater effects on environmental lifetime than on cost or embodied GHG emissions. The median MIs for cost or embodied GHG emissions spanned less than one order of magnitude. In contrast, the MI for environmental lifetime spanned nearly three (**Figure 1C**). While polyethylene terephthalate (PET), polylactic acid (PLA), and polypropylene (PP) optimized indices for cost and embodied GHG emissions relatively well, these materials were poor choices for minimizing environmental lifetime. Polybutylene adipate terephthalate (PBAT) was one of the poorest choices for each MI. Comparatively, CDA, PA, PCL, PHA, and PUR had greater values of the MI for cost (i.e., more expensive than

131 polyolefins), and variable values of the MI for embodied GHG emissions (i.e., CDA and PCL
132 were lower, and PA, PHA, and PUR were higher than polyolefins). These same materials,
133 though, had properties that reduced the MI for environmental persistence (i.e., shorter lifetimes
134 than polyolefins).



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136 **Figure 1. Designing a stiff beam with minimal environmental lifetime at end-of-use.** (**A**)
137 Schematic of a simply-supported beam. (**B**) Selection chart for environmental lifetime. Dashed

lines indicate contours of equivalent performance for the MI. The arrow indicates the direction of better performance. Values of k_d are for seawater (marine) conditions with and without sunlight. Values are the combination of laboratory, mesocosm, and field experiments. Data for k_d are presented as mean ± maximum and minimum values. Data for the Young's modulus (E) are presented as the median value. (**C**) Tradeoff chart comparing MIs. $M_1 = \frac{C_m \rho}{E^{1/2}} [\frac{\$USD}{m^3 \cdot MPa^{1/2}}]$, $M_2 = \frac{C_{GHG} \rho}{E^{1/2}} [\frac{kg\ CO_2-eq}{m^3 \cdot MPa^{1/2}}]$, and $M_3 = \frac{1}{k_d E^{1/4}} [\frac{yr}{mm \cdot MPa^{1/4}}]$. Data are presented as median values. Data are available in **Tables S2-S5 and S7-S9**.

While MIs are helpful, they cannot, on their own, quantify the tradeoffs between competing design objectives. To address this, value functions can be used to systematically weigh the relative value of any given combination of MIs by forming a compound objective for optimization.[30] Value functions are defined by converting the performance (e.g., mass, energy, time) to value (e.g., monetary value or cost) using exchange constants (e.g., price per kg). Despite the challenges in determining them, several exchange constants for environmental impact have been proposed (**Table S10**).

Because plastic products can persist in the environment as pollution, their impact is cumulative every year they remain. Therefore, we propose that the cost of plastic pollution (C_P) i.e., its value, can be defined as a performance-exchange constant pair of environmental lifetime and the cost of plastic pollution per mass of material per year in the environment. Accordingly, the cost of plastic pollution is realized as the product of the exchange constant (α_L) and the integrated mass over a product's environmental lifetime (**Equation 5**), where m is the instantaneous mass of the product from when it first entered the environment ($t = 0$) to when it is completely degraded ($t = t_L$).

$$C_P = \alpha_L \chi_P f_P \int_{t=0}^{t_L} m\, dt \tag{5}$$

For the value of α_L we propose using the economic cost of plastic pollution, estimated to be between $3300 and $33000 per metric ton of marine plastic per year (2011 $USD).[31] This term underestimates the total cost of plastic pollution, as it only considers the toll on marine ecosystems, not the complete biosphere. To acknowledge that not every item leaks into the environment, we adjusted C_P by multiplying by the total fraction of plastic leaking into the environment (χ_P) and by the fraction with which a given type of item would contribute to the total amount of leaked plastic (f_P).[32,33] Presently, society, not the manufacturer, bears the cost of plastic pollution, requiring discussions of policies for extended producer responsibility to acknowledge this cost.

For most geometries (those that retain the same morphology as they degrade), **Equation 5** can be approximated by **Equation 6** where m_0 is an item's initial mass, and n is a dimensionless 'shape factor' (n is 1 for films, 2 for solid cylinders and beams, and 3 for spheres) (**Section S3**).

$$C_P = (\alpha_L \chi_P f_P)\left(\frac{m_0 t_L}{n + 1}\right) \tag{6}$$

Application to Single-Use Plastics: Disposable Coffee Cup Lids.

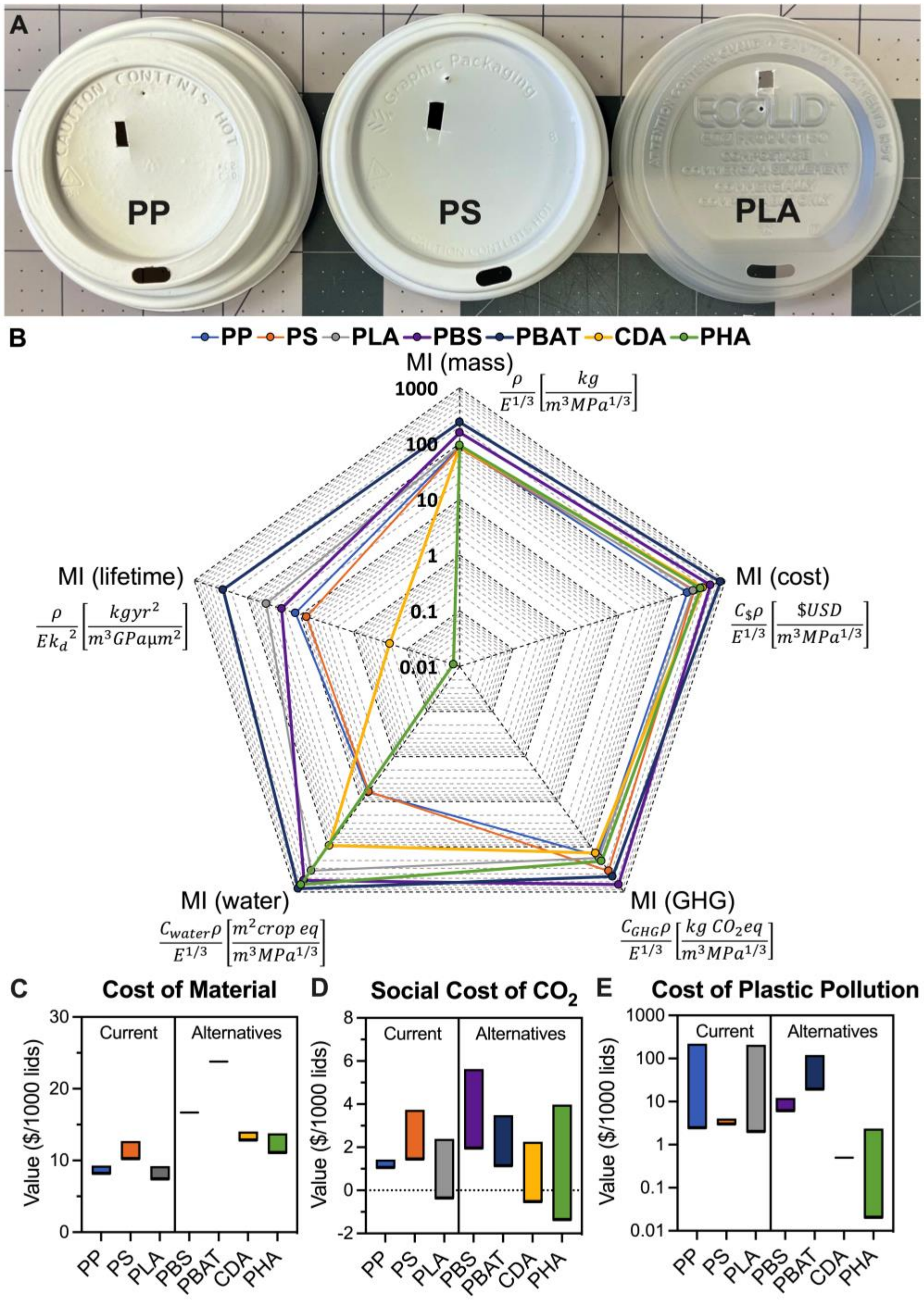
Currently, billions of disposable coffee cup lids are used annually[34] of which a fraction become pollution, accounting for ~5% of plastic debris in nearshore waters.[33] Thus, any savings from their environmental impact can yield significant benefits. In this section, we use our framework to evaluate which on-the-market lid material reduces the environmental impact the most and determine which next-generation plastics are best and thus warrant adoption.

Today, disposable coffee cup lids are made from PLA, PP, or PS (**Figure 2A**); which material "best" reduces environmental impact, however, is non-obvious. Comparing MIs for several environmental impact categories included in LCAs[4,8,35] indicated that of the three materials, PP was the best. PP minimized MIs for GHG emissions and water usage (**Figure 2B**). Ironically, PP is one of the most abundant types of plastic found in marine garbage patches.[36] Calculated value as the sum of the cost of material and the social cost of CO_2 per 1000 lids expressed in 2016 $USD for PP, PS, and PLA ranged from $9.17 to $10.72 for PP, $11.61 to $16.46 for PS, and $6.99 to $11.60 for PLA (**Figures 2C-D**). Thus, overall, no material was much better than another. Though abridged, the result is not expected to change, given that conventional LCA impact categories trend well with GHG emissions.[35,37]

Lid design should account for persistence. Of the three materials, PS was optimal for environmental lifetime (**Figure 2B**). Including persistence (cost of plastic pollution) could increase the cost per 1000 lids expressed in 2016 $USD for PLA and PP to over $200 while increasing the cost for PS to ~$20. Our analyses suggest that PS may be the least impactful of the three materials on the market for disposable lids.

Our metric provides an opportunity not only to compare materials in use but also to identify less environmentally impactful alternatives. CDA, PBAT, PBS, and PHA are championed by many as alternative, more sustainable, degradable plastics for making consumer products.[38,39] Comparing MIs, disposable lids made of CDA or PHA could provide more than an order of magnitude better performance for environmental lifetime while being comparable in other categories (**Figure 2B**). PBAT and PBS were worse than current plastics for nearly all MIs (**Figure 2B**). This result underscores the idea that bio-based, biodegradable, or compostable plastics are not a panacea for addressing the environmental impacts of plastics.[40,41] Instead, our results suggest that a more nuanced understanding is needed, whereby some biobased plastics are robust alternatives (i.e., CDA and PHA), and others appear to exacerbate the problem (i.e., PBAT and PBS).

Notably, without accounting for persistence, the incentive to switch to these alternative plastics is weak, given their increased cost and limited reductions in GHG emissions (if at all) compared to current plastics (**Figures 2C-D**). However, adopting alternatives could be incentivized by the value gained by reducing the cost of plastic pollution. Savings to the cost of pollution per 1000 lids from switching to CDA or PHA compared to current plastics were estimated to range from $1.46 to $220.01 and -$0.40 to $220.49, respectively (**Figure 2E**). Given the billions of lids consumed annually,[34] these savings could translate to societal benefits of hundreds of millions of dollars for this item.



217 **Figure 2. Selecting materials for disposable coffee cup lids.** (**A**) Current lids on the market. (**B**) 218 Radar plot comparing MIs for mass, cost, embodied GHG emissions, water usage, and 219 environmental lifetime of current and potential alternative plastics. Data are presented as the 220 median values. (**C**) Comparison of the cost of material, (**D**) the social cost of CO_2, and (**E**) the cost

of plastic pollution for current and potential alternative plastics. The social cost of CO_2 is the estimated societal damage due to anthropogenic CO_2 emissions. Data are presented as the minimum and maximum calculated values. Data used for the calculations are available in **Tables S2-S8 and S11-S13**. For the derivation of the MI for environmental lifetime of a lid, see **Section S4**.

Current Limitations of the Specific Surface Degradation Rate (k_d).

Our framework shows promise for designing more ecocompatible[42] plastic products; however, informed decisions will only be as good as the data used to make them. While many studies have investigated degradation, a limited number have reported information sufficient to calculate k_d. Additionally, several studies were conducted using closed-system bottle incubations, which can lack environmental relevance because the plastic in question is used as the sole nutrient source of carbon.[43] Results of these studies often report much faster degradation rates than those from more realistic mesocosm and field experiments (**Table S7**). Moreover, the few reports of k_d pale compared to the vast number of plastic formulations contributing to the large variability across plastic types. For example, in the case of PHAs (**Figure 1**), k_d values span nearly two orders of magnitude. Consequently, while PHAs could be materials with the least cost of pollution (**Figure 2E**), they could also be some of the more costly choices. In the case of PA, only one study has measured k_d (**Table S7**), making any estimate of PA lifetime and cost of pollution highly uncertain. Such tremendous variability and uncertainty pose significant challenges to material selection.

Moreover, while some studies demonstrate that k_d represents the mineralization of plastic to carbon dioxide, dissolution to dissolved organic carbon, or assimilation to biomass,[14] many studies present no evidence of complete or partial transformation.[13] This poses challenges in knowing whether k_d represents the chemical degradation (depolymerization) of the polymer or merely the physical degradation (disintegration) to microplastics. Regardless of the degradation process, the impacts of any degradation products released from plastic items must also be considered.[44,45] Finally, a key challenge is that the molecular and microstructural features underpinning polymer degradation[46] also control many other polymer properties (e.g., Young's modulus).[47] Of the studies reporting data sufficient to calculate k_d, less than half included characterization of any physical and mechanical properties or provided enough details to determine them after the fact. Because the environmental lifetime of an item can depend on k_d and other material properties, making effective material selection decisions will require reporting comprehensive details of material properties along with k_d.

The metric we propose for minimizing environmental lifetime applies to mitigating terrestrial plastic pollution and waste destined for landfill or composting, although similar data limitations exist for k_d in these environments.[13] Overall, a greater understanding of the environmental controls (e.g., sunlight exposure, temperature, nutrients, microbial communities) and structure-property-formulation relationships governing plastic degradation will improve predictions of k_d and resulting lifetime and cost of pollution estimates.

Optimizing Environmental Degradation Through Consideration of Additives and Form Factors.

Plastics are polymers modified with organic and inorganic additives, constituting their formulation.[48] Various compounds added to plastics or included in them as non-intentionally added substances can facilitate or inhibit the environmental degradation of plastics. For example, antioxidants and ultraviolet light stabilizers are added to plastics to protect them from thermal degradation during processing and photochemical degradation during outdoor use.[49,50] Because plastics are typically thermally processed, most plastic products contain antioxidants,[51] which can prolong plastic lifetimes compared to additive-free plastics. Other additives can intentionally (e.g., pro-oxidants,[50] photocatalysts,[52] enzymes,[53] or microbes[54]) or inadvertently (e.g., pigments[45], catalyst residues, and unsaturated bonds[21]) enhance degradation. Additionally, the amount of polymer used to make a product can be reduced using fillers, thereby reducing lifetimes in proportion to the amount of filler used.[25] While additives may prove helpful for reducing environmental lifetimes, their potential harm to human health and the environment must also be appreciated.[55] Moreover, the intrinsic toxicity of plastic will require an MI to inform design decisions. Ecocompatible plastics must be made from ecocompatible polymers and ecocompatible additives.

A product's degradation rate is controlled by material and geometry (i.e., surface area). It should be standard practice for engineers to use topology optimization techniques and additive manufacturing to design and fabricate products that maximize surface area and thus minimize environmental lifetime. Such strategies have already begun to be applied to some single-use items (e.g., cutlery[56]) by redesigning them to remove structurally unnecessary material. Lattice-filled or foamed structures also achieve this objective. In particular, foamed items may have added benefits by keeping them in conditions more favorable to degradation because of their positive buoyancy and, thus, exposure to sunlight. Addressing the plastic pollution crisis will need less persistent plastics and innovative approaches to product form to achieve effective eco-designs.

Impacts on Workforce Development, Consumers, and Global Policy.

Engineering programs accredited by the Accreditation Board for Engineering and Technology (ABET) are required to teach environmental design considerations[57]; however, most engineering students do not receive training on the persistence of materials in the environment. According to ABET review criteria, only environmental engineering curricula are explicitly required to teach about the fate and transport of materials in the environment.[57] This limited specificity in accreditation criteria is reflected in practice. For example, a review of 24 undergraduate material science and engineering programs (with or without ABET accreditation) across research-intensive universities (R1) in North America demonstrated that eco-design might only be taught within ~30% of material selection courses (**Data S1**). Thus, ~70% of engineers may enter the workforce without receiving mandatory curricular instruction on the environmental impact of materials and their tradeoffs. Incorporating our novel metric and others (e.g., for microplastic formation[58]) into material selection and design courses thus represents an opportunity to train the next generation of engineers about eco-design and close the sustainability gap in materials education.[59]

Local communities have already begun regulating single-use plastic products (e.g., bans on straws, grocery bags, and bottles).[60] Yet often, consumers are without recommendations for products made from alternative materials.[61] Like product designers, consumers need strategies for making the "best" material selection choices for the environment. We recommend implementing a simple, quantitative persistence label for plastic products that can complement existing eco-labels (e.g., Energy Star) to inform consumers about the persistence of plastic materials in the environment.

Globally, negotiations for an international plastics treaty are underway. The eco-design framework presented herein for mitigating environmental persistence should be considered part of the resolution. Material indices provide quantitative metrics for benchmarking materials during the design process that could be integrated with other sustainability metrics[8] to define regulatory criteria in policy.

ASSOCIATED CONTENT

Supporting Information.

The following files are available free of charge.

Materials and methods; Section S1 deriving a material index; Section S2 deriving a material index for persistence; Section S3 derivation of Equation 6; Section S4 derivation of a material index for persistence of a coffee cup lid; Table S1 common material indices; Table S2 density of common plastics; Table S3 Young's modulus of common plastics; Table S4 specific price of common plastics; Table S5 embodied greenhouse gas emissions of common plastics; Table S6 embodied water usage of common plastics; Table S7 specific surface degradation rates of common plastics; Table S8 summary of specific surface degradation rates; Table S9 calculated material indices of common plastics; Table S10 exchange constants; Table S11 properties of disposable coffee cup lids; Table S12 properties of hypothetical disposable coffee cup lids; Table S13 data presented in Figures 2C-E; Additional references (PDF).

Data S1 results of material selection course survey (XLSX).

AUTHOR INFORMATION

Corresponding Author

***Bryan D. James** – Department of Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, United States; Email: bjames@whoi.edu

Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Conceptualization: BDJ, CPW, CMR

Methodology: BDJ

Investigation: BDJ

Visualization: BDJ, CPW, CMR, MEH, SJT

Funding acquisition: BDJ, CPW, CMR, MEH

Project administration: BDJ, CPW, CMR, MEH

Supervision: BDJ, CPW, CMR, MEH

Writing – original draft: BDJ, CPW, CMR, MEH, SJT

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Notes

The authors declare that they have no competing interests. All data are available in the main text or the supplementary materials.

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ABBREVIATIONS

PET, polyethylene terephthalate; PA, polyamide; PHA, polyhydroxyalkanoate; PLA, polylactic acid; PS, polystyrene; PCL, polycaprolactone; PC, polycarbonate; PBS, polybutylene succinate; PBAT, polybutylene adipate terephthalate; PP, polypropylene, LDPE, low-density polyethylene; HDPE, high-density polyethylene; CDA, cellulose diacetate; PUR, polyurethane.

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