ACS Sustainable Chemistry & Engineering

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Letter

Minimizing the Environmental Impacts of Plastic Pollution through Ecodesign of Products with Low Environmental Persistence

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Cite This: *ACS Sustainable Chem. Eng.* 2024, 12, 1185−1194

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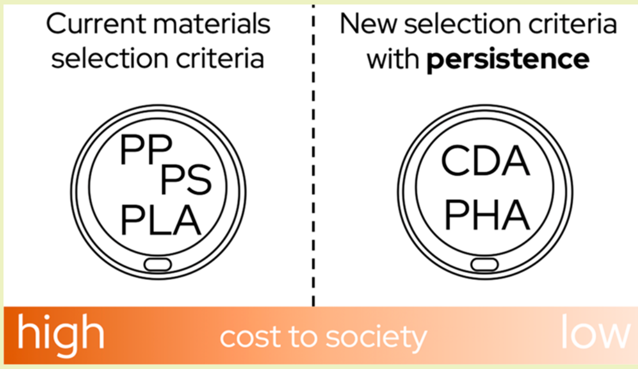
ABSTRACT: While plastic pollution threatens ecosystems and human health, the use of plastic products continues to increase. Limiting its harm requires design strategies for plastic products informed by the threats that plastics pose to the environment. Thus, we developed a sustainability metric for the ecodesign 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 the environmental persistence of plastics in design could translate to societal benefits of hundreds of millions of dollars for a single consumer product. Our analysis identifies the materials and their properties that deserve development, adoption, and investment to create functional and less environmentally impactful plastic products.



KEYWORDS: *plastic pollution, biodegradation, material selection, life cycle assessment, persistence, degradable polymers, sustainability, green chemistry and engineering*

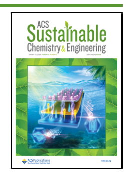
INTRODUCTION

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, renewable, and circular.[3] Design decisions rely on ecodesign, green chemistry and engineering principles, life cycle assessments (LCA), and related methods to reduce a product's environmental impact.[4−13] A recent U.S. National Academies of Sciences, Engineering, and Medicine report identifies material and product design as one of six key interventions to reduce plastic pollution.[14] However, plastics and their adverse effects on humans and the environment challenge current approaches to the design of sustainable products. In general, materials are primarily selected by balancing trade-offs between environmental impact categories, such as greenhouse gas (GHG) emissions and resource depletion, because frameworks (e.g., ISO 14040:2006) and data sets (e.g., ecoinvent[15]) have been established for estimating these impacts.[8,12,13] However, environmental persistence, defined as the time a plastic item lasts in the environment as pollution, is missing from material selection criteria (e.g., in LCA[16,17]).

While plastics do break down in the environment,[18−27] 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.[18,26,27] The efficiency and selectivity of these processes depend on environmental conditions, the type of plastic, and the functionality and geometry of the product,[18] 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 and end-of-life strategies, it is necessary to confront their persistence.[28−31]

With the understanding that more persistent materials pose greater potential threats to ecosystems and human health,[29,30,32] environmental persistence is a fundamental principle of regulatory frameworks, and green chemistry and engineering.[6,33,34] Therefore, considering persistence during product design by selecting materials that quickly break down when leaked into the environment presents an opportunity to

Received: August 30, 2023
Revised: November 30, 2023
Accepted: December 1, 2023
Published: January 8, 2024



https://doi.org/10.1021/acssuschemeng.3c05534
ACS Sustainable Chem. Eng. 2024, 12, 1185−1194

minimize risks to ecosystems and human health. Recent measurements of environmentally realistic plastic degradation rates catalyze this thinking. Here, we aggregate concepts learned from the past decade of plastic pollution research and integrate them into established material selection practices, elevating a quantitative, multidimensional ecodesign framework for minimizing the environmental impacts of plastic pollution.

■ MATERIALS AND METHODS

Material property data were collated from primary sources and databases to determine the range of density (ρ), Young's modulus (E), specific price, specific embodied greenhouse gas (GHG) emissions, and specific embodied water usage for each plastic investigated. Data sources for each property and plastic are referenced in Tables S1–S5. Specific surface degradation rate (k_d) data were calculated from primary reports and collated from reviews in the peer-reviewed literature. Data sources for each value of k_d are referenced in Table S6 and summarized for each plastic in Table S7. Extended materials and methods are included in the Supporting Information.

■ RESULTS AND DISCUSSION

Selecting appropriate materials is critical for engineers,[35] industrial designers,[36] and architects[37] to create functional and aesthetically pleasing products. According to Ashby,[38] 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).[35]

A Material Index for Persistence. To date, no material selection framework has considered or quantified environmental persistence. Coincidentally, missing 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,[18] herein, we limit the definition of degradation to overall mass loss from the initial plastic item in an environmental medium (e.g., seawater or soil).

Complementary to this, we define environmental lifetime as the time it takes for an item's mass to decrease to zero due to degradative processes. Accordingly, we propose that persistence can be included in material selection by considering the design objective to minimize the environmental lifetime if leaked into the environment. Much like other MIs (Table S8, 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 align with the methods of Ashby,[38] we first demonstrate our approach using the example of a stiff beam (Figure 1A). A typical function of a beam is to support a load without sagging. Rather than minimize the beam's mass or cost, the design objective is to minimize the beam's environmental lifetime if it leaked into the environment. The design constraints on the beam define the loading conditions, the 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

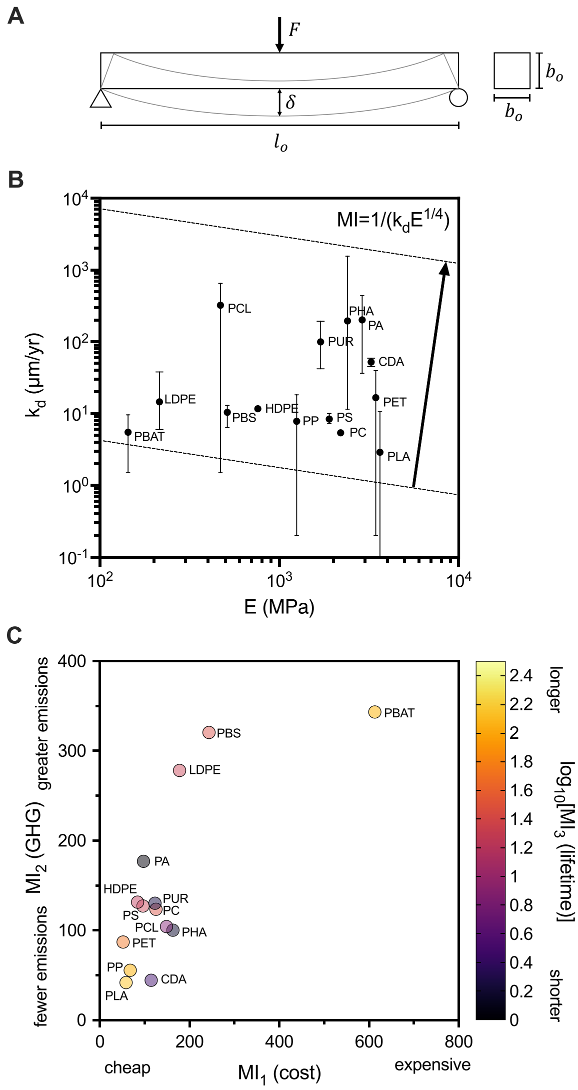


Figure 1. Designing a stiff beam with minimal environmental lifetime if leaked into the environment. (A) Schematic of a simply supported beam. (B) Material property chart of the specific surface degradation rate (k_d) and Young's modulus (E). Dashed lines indicate contours of equivalent performance for 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 the mean ± maximum and minimum values. Data for E are presented as the median value. (C) Trade-off chart comparing MIs. Note that MI_3 is presented using a base 10 logarithmic scale. $MI_1 = \frac{C_m\rho}{E^{1/2}}\left[\frac{\$\,USD}{m^3{\cdot}MPa^{1/2}}\right]$, $MI_2 = \frac{C_{GHG}\rho}{E^{1/2}}\left[\frac{kg\,CO_2 - eq}{m^3{\cdot}MPa^{1/2}}\right]$, and $MI_3 = \frac{1}{k_d E^{1/4}}\left[\frac{yr}{mm{\cdot}MPa^{1/4}}\right]$. Data are presented as median values (Table S9).

by solving a degradation rate equation, establishing a mathematical relationship between the 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 $\left(\frac{dm}{dt}\right)$, equal to the product of the surface area (A_s) of

https://doi.org/10.1021/acssuschemeng.3c05534
ACS Sustainable Chem. Eng. 2024, 12, 1185−1194

the item and the density (ρ) and specific surface degradation rate (k_d) of the item's material (eq 1).[18]

$$\frac{dm}{dt} = -\rho k_d A_s \tag{1}$$

In this formulation, k_d is a phenomenological parameter that assumes that all mass loss is by surface erosion. Notably, this framing implies that intrinsic properties of the material (e.g., density) 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[18]).

Assuming a solid beam with a square cross-section, we solved eq 1 (Section S2) to yield a relationship between environmental lifetime (t_L), the initial edge length of the cross-section (b_0), and k_d (eq 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 S1), 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) (eq 3).

$$b_0 = \left(\frac{12Fl_0^{\,3}}{C_1E\delta}\right)^{1/4} \tag{3}$$

Substituting eq 3 into eq 2 relates the environmental lifetime in terms of the design constraints (eq 4). For more complex items, numerical methods (e.g., finite element simulations) can be used to solve eq 2 for determining relationships between environmental lifetime and material properties, as done for other MIs.[39]

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

Grouping the terms for material properties expressed in eq 4, the MI for minimizing the persistence of a beam with a solid square cross-section is $\frac{1}{k_dE^{1/4}}$. This MI implies that designing a beam optimized for environmental lifetime requires considering a material's k_d and E. While this MI for persistence was derived with respect to a mechanical constraint, these MIs can be derived with respect to any design constraint (e.g., thermal, electrical, etc.).

By using the reported values for k_d and E of several plastics, the materials that yield a functional beam optimized for environmental persistence can be determined. 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.

Trade-offs between Competing Design Objectives. In practice, products must satisfy multiple, often competing design objectives. For the ecodesign of a plastic product, design objectives must aim to optimize function, cost, and metrics related to environmental impact and circularity (Table 1).

Table 1. Sustainability Metrics for the Ecodesign of Plastic Products

theme	metric	green design principles[11,a]
persistence (this work)	MI for minimizing environmental lifetime	GC: 10
	form efficiency	GE: 1, 7
energy efficiency[40]	MI for minimizing embodied energy[12]	GC: 6
		GE: 3, 4, 10
material efficiency[41,42]	MI for minimizing mass	GE: 4, 8
	form efficiency[43,44]	
waste reduction	production efficiency[11,45]	GC: 1
		GE: 4
global warming potential	MI for minimizing embodied GHG emissions[13]	GC: 1
	LCA metrics[11]	GE: 2
resource depletion	MI for minimizing embodied water usage[45]	GE: 4
	MI for minimizing embodied land usage[45]	
	LCA metrics[11]	
toxicity[46]	plastic hazard ranking[47]	GC: 1, 3, 4, 5
	microplastic index[48]	GE: 1, 2
	LCA metrics[11]	
renewable feedstocks[11]	fraction of renewable feedstock used	GC: 7
	distance to feedstocks	GE: 10, 12
recyclability[45]	material complexity (e.g., number of materials)[49]	GE: 4, 6, 9, 11
	form factor (e.g., solid, film, foam)[49]	
	fraction of recycled content in current supply	
	recycling efficiency	
end-of-life management	fraction recoverable	GE: 3, 6, 11
	availability of infrastructure for circularity	

[a]GC = green chemistry; GE = green engineering.

Comparing Material Indices. To illustrate the trade-offs between common design objectives (cost and embodied GHG emissions) and the new objective to minimize environmental lifetime, we calculated MIs for the beam example presented in the previous section using literature data for several plastics. The choice of material had a much greater effect on the environmental lifetime than on cost or embodied GHG emissions. The median MIs for cost or embodied GHG emissions spanned less than 1 order of magnitude. In contrast, the MI for environmental lifetime spanned nearly three (Figure 1C). While poly(ethylene 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 polyolefins) and variable values of the MI for embodied GHG emissions (i.e., CDA and PCL were lower and

https://doi.org/10.1021/acssuschemeng.3c05534
ACS Sustainable Chem. Eng. 2024, 12, 1185−1194

PA, PHA, and PUR were higher than polyolefins). These same materials, however, had properties that reduced the MI for environmental persistence (i.e., shorter lifetimes than polyolefins).

Evaluating Value Functions and the Cost of Plastic Pollution. While MIs are helpful, they cannot express the trade-offs in economic value 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.[50,51] Value functions are defined by converting the performance (e.g., mass, energy, and 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).

To evaluate the trade-offs between persistence and other design objectives requires creating a value function that quantifies the cost of a plastic product persisting in the environment. Because plastic products can persist in the environment as pollution, their impact is cumulative every year that 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 (eq 5), where m is the instantaneous mass of the product from when it first entered the environment (t = 0) to when it is wholly degraded ($t = t_L$).

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

For the value of α_L we propose using the decline in marine ecosystem services due to plastic pollution, estimated to be between \$3300 and \$33000 per metric ton of marine plastic per year (2011 \$USD)[52] as an initial exchange constant for the cost of plastic pollution. This term underestimates the total cost of plastic pollution, as it considers only the toll on marine ecosystems, not the complete biosphere. Presently, society, not the manufacturer, bears the cost of plastic pollution, requiring discussions of policies for extended producer responsibility to acknowledge this cost.

As others have acknowledged that not every item leaks into the environment,[53] we adjusted C_P by multiplying it by the total fraction of plastic leaking into the environment (χ_P) and the fraction with which a given type of item would contribute to the total amount of leaked plastic (f_P).[54,55] Thus, for items that rarely leak into the environment, their associated value of f_P is small, reducing the cost of plastic pollution. Therefore, the contribution to the total cost of the item due to its persistence will be little. In such a situation, the need to address persistence in the design of such an item will be less compared with an item that has a much larger value of f_P.

For most geometries (those that retain the same morphology as they degrade), eq 5 can be approximated by eq 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).

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

Application to Single-Use Plastics: Disposable Coffee Cup Lids. Currently, billions of disposable coffee cup lids are used each year[56] and account for ∼5% of plastic debris in nearshore waters.[55] Thus, any economic savings from their environmental impact can yield significant benefits. In this section, we use several sustainability metrics (Table 1) and a multicomponent value function 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 (Supporting Information).

Comparing Materials on-the-Market. Today, disposable coffee cup lids are made from PLA, PP, or PS (Figure 2A);

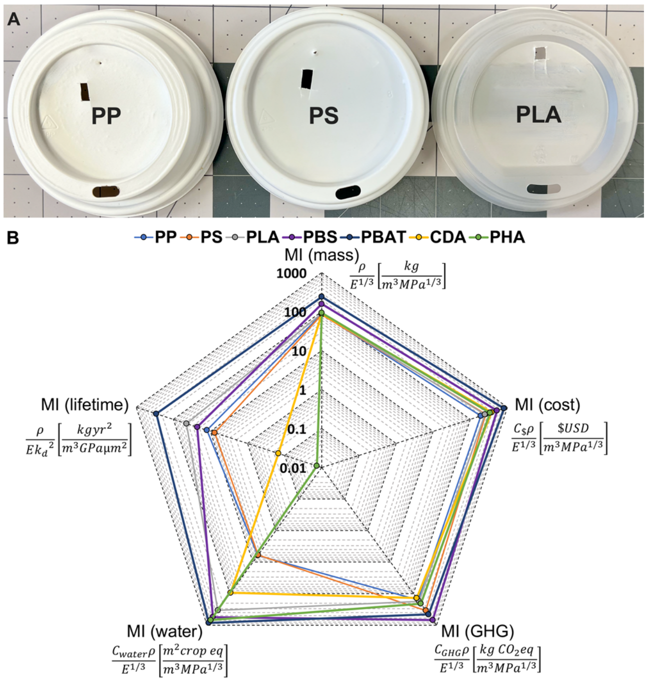


Figure 2. Selecting materials for disposable coffee cup lids using MIs. (A) Image of current lids on the market. Logos and other text have been digitally blurred. (B) Radar plot comparing MIs for mass, cost, embodied GHG emissions, embodied water usage, and environmental lifetime of current and potential alternative plastics. Data are presented as median values. Data used for the calculations are available in Tables S1−S7. For the derivation of the MI for the environmental lifetime of a lid, see section S4.

which material "best" reduces environmental impact, however, is not obvious. Considering material circularity, each plastic can be produced using renewable feedstocks and diverted from a linear end-of-life disposal route. However, the majority of PP and PS are derived from petroleum sources, and most of these materials are disposed of in landfills or by incineration.[14,57] PLA can be industrially composted, opening up a greater possibility for circularity, as it is almost exclusively synthesized using renewable feedstocks. Yet, this is hampered by a lack of access to and availability of a composting infrastructure.[58] Comparing MIs for several environmental impact categories included in LCAs[4,11,59] indicated that of the three materials, PP was the best. PP minimized MIs for GHG emissions and water use (Figure 2B). Though abridged, the result is not expected to change, given that conventional LCA impact categories trend

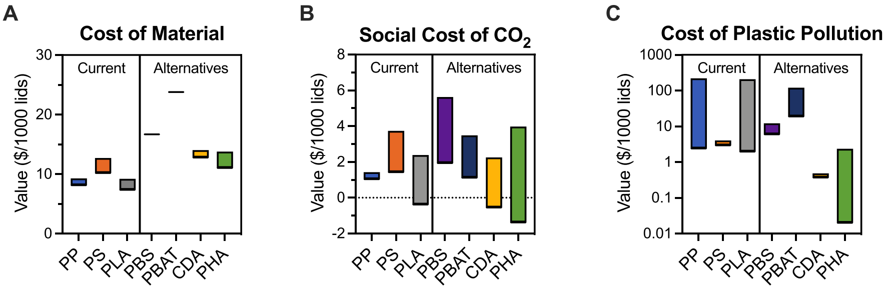


Figure 3. Selecting materials for disposable coffee cup lids using value functions. Comparison of (A) the cost of material, (B) the social cost of CO_2, and (C) the cost of plastic pollution for current and potential alternative plastics. The social cost of CO_2 is estimated societal damage due to anthropogenic CO_2 emissions. Materials, methods, and data used for the calculations are available in the Supporting Information and Tables S1−S7, S11−S12. Data are presented as the minimum and maximum calculated values (Table S13).

well with GHG emissions.[59,60] Thus, overall, no material was much better than another when evaluated using current metrics for ecodesign (Table 1).

Lid design should account for persistence because a substantial number of these items leak into the environment.[55] Of the three materials, PS was optimal for environmental lifetime (Figure 2B). From a value perspective (Supporting Information), 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 3A-B). Including persistence (cost of plastic pollution) could increase these costs for PLA and PP to over $200 while increasing the cost for PS to ∼$20 (Figure 3C). Based on the available data and the proposed metrics, our analyses suggest that PS may be the least impactful of the three materials on the market for disposable lids. As noted, this is based on what we know now and is subject to change.

Identifying Less Impactful Alternatives. Our framework 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.[61−63] 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). Additionally, CDA and PHA can be derived from renewable feedstocks and integrate into a circular economy.[61] PBAT and PBS were worse than the current plastics for nearly all MIs (Figure 2B). This result underscores the idea that biobased, biodegradable, or compostable plastics are not a panacea for addressing the environmental impacts of plastics.[64−66] 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 3A-B). Other properties captured by green engineering principles, such as the ease of material recovery, recyclability, and circularity, may also provide incentives to switch;[67−69] however, the broad implementation of these favorable attributes in ecodesign is currently hindered by a lack of waste recovery and recycling infrastructure[14,57,70] and global disparities in waste management practices.[54,71−73] Instead, adopting alternatives could be incentivized by the inherent value gained by reducing the cost of plastic pollution (Supporting Information). Savings to the cost of pollution per 1000 lids from switching to CDA or PHA compared to current plastics were estimated to range from $1.48 to $220.14 and −$0.40 to $220.49, respectively (Figure 3C). Given the billions of lids consumed annually,[56] these savings could translate to societal benefits of hundreds of millions of dollars for this one item, implying even greater benefits by applying this approach more broadly to the collection of frequently mismanaged plastic products.

Current Limitations and Research Needs for the Specific Surface Degradation Rate (k_d). Our framework shows promise for designing more ecocompatible[74] 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.[75] Results of these studies often differ substantially from more realistic mesocosm and field experiments (Table S6). Moreover, the few reports of k_d pale compared to the vast number of plastic formulations contributing to the large variability within and across plastic types. For example, in the case of PHAs (Figure 1), values of k_d span nearly 2 orders of magnitude. Consequently, while PHAs could be materials with the least cost of pollution (Figure 3C), they could also be some of the more costly choices. In the case of PA, PC, and PUR, only two to three studies have measured k_d for each plastic (Table S6), making any estimate of their lifetimes and costs of pollution highly uncertain. Such tremendous variability and uncertainty pose significant challenges to material selection, making measurements of k_d conducted under environmentally relevant mesocosm and field conditions a research priority moving forward.

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,[19] many studies present no evidence of complete or partial transformation.[18] This poses challenges in knowing whether k_d represents the chemical degradation (depolymerization) of the polymer or merely the physical degradation (disintegration) to microplastics. Future research should prioritize the relative importance and controls of plastic degradation processes and products, as well as the environ-

https://doi.org/10.1021/acssuschemeng.3c05534
ACS Sustainable Chem. Eng. 2024, 12, 1185−1194

mental impacts (e.g., ecotoxicity) of any degradation products and leachable compounds released from plastics into the environment.[76,77]

Finally, a key challenge is that the molecular and microstructural features underpinning polymer degradation[78] also control many other polymer properties (e.g., Young's modulus).[79,80] 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 the material's properties, along with k_d. Moreover, MIs for environmental persistence identify the material properties, along with k_d, that should be prioritized when designing novel polymers.

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.[18,81] Moreover, k_d will be a significant parameter for the reliable design of biodegradable plastic products (e.g., transient electronics[82−86] and biomedical devices[87−89]), in which the end-of-life disposal is the partial or complete degradation of the item. For these applications, k_d is paramount to the prediction and design of their useful lifetime in degrading environments.[90] 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 estimates of environmental lifetime and cost of pollution.[31]

Optimizing the Environmental Degradation of Plastics by Considering Formulation and Form Factor. Regardless of any improvement in our waste management systems, leakage of plastics into the environment is unavoidable. Addressing the persistence of a product early in the design stage can alleviate its potential impact due to accidental leakage by inherently reducing its residence time in the environment and thus its associated ecological risks. Nevertheless, it is critical to communicate to consumers that the design of plastic products for minimal persistence does not justify their disposal in the environment. By designing plastic products for minimal environmental persistence, the reduction in their potential ecological risk changes from being circumstantial (i.e., relying on uncertain consumer behavior and varying waste management systems) to being inherent (i.e., addressing the risks posed by improper disposal directly through product design).[29]

Plastic products can be designed for environmental degradation by optimizing their materials and form. Plastics are polymers modified with organic and inorganic additives, constituting their formulation.[91] Throughout, we have only considered plastics composed of a single polymer type; however, evidence shows that polymer blends and copolymers can synergize or antagonize environmental degradation, broadening the range of potential k_d.[92−94] Various compounds added to plastics or included in them as nonintentionally added substances can facilitate or inhibit the environmental degradation of plastics. For example, antioxidants and ultraviolet-light stabilizers are added to plastics to limit thermal degradation during processing and photochemical degradation during outdoor use.[95,96] Because plastics are typically thermally processed, most plastic products contain antioxidants,[97] which can prolong plastic lifetimes compared to additive-free plastics. Other additives can intentionally (e.g., pro-oxidants,[98] photocatalysts,[99] enzymes,[100] or microbes[101]) or inadvertently (e.g., pigments,[77] catalyst residues, and unsaturated bonds[26]) enhance degradation. Additionally, the amount of polymer used to make a product can be reduced by using fillers. While plastic formulations can be designed to control degradation rates, their complexity must be balanced with the challenges that ever more complex and diverse formulations pose to recycling methods.[49] Developing MIs that relate a plastic product's function to its recyclability will enable the design of more circular items. While additives may prove helpful for reducing environmental lifetimes, their potential harm to human health and the environment must also be appreciated.[46] Moreover, the intrinsic toxicity of plastic will require an MI to inform design decisions. Ecocompatible plastics must be formulated from ecocompatible polymers and ecocompatible additives.

The degradation rate of a plastic product is expected to be controlled by material and form (i.e., surface area). It should be standard practice for engineers to use topology optimization techniques[102] 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[103]) by redesigning them to remove structurally unnecessary material. Lattice-filled or foamed structures also achieve this objective. For example, it was recently demonstrated that a foamed CDA drinking straw has at least 2-fold lower persistence in the coastal ocean than its solid counterpart.[104] Foamed items may also have added benefits by keeping them in conditions more favorable to degradation because of their buoyancy and thus exposure to sunlight. Nonetheless, product form affects many sustainability metrics (Table 1); thus, design changes that reduce a product's environmental lifetime must be balanced alongside form factors that enable circular designs.

Scientists, engineers, and designers have an opportunity to intervene in curbing plastic pollution. The metrics (Table 1) and methods put forth can direct their design decisions and research priorities toward these ideals. This framework will continue to improve with further research on the environmental impacts of plastics, particularly through the robust measurement of plastic degradation under realistic environmental conditions. Ultimately, minimizing the persistence of mismanaged plastic products will require innovative plastic formulations and product form factors, along with concerted effort across the plastic life cycle to mitigate leakage.

■ ASSOCIATED CONTENT

Data Availability Statement

All data are available in the main text or the Supporting Information.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.3c05534.

Section S1 deriving a material index; section S2 deriving a material index for persistence; section S3 derivation of eq 6; section S4 derivation of a material index for persistence of a coffee cup lid; Table S1 density of common plastics; Table S2 Young's modulus of common plastics; Table S3 specific price of common plastics; Table S4 embodied greenhouse gas emissions of common plastics; Table S5 embodied water usage of common plastics; Table S6 specific surface degradation rates of common plastics; Table S7 summary of specific surface degradation rates; Table S8 common material indices; 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 3A-C; additional references (PDF)

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The manuscript was written with contributions from 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. Writing−review and editing: BDJ, CPW, CMR, MEH, SJT.

Funding

This work was supported by the Postdoctoral Scholar Program at the Woods Hole Oceanographic Institution (WHOI), with funding provided by the Weston Howland Jr. Postdoctoral Scholarship (BDJ). Additional support was provided by the WHOI Ocean Vision Fund 2030 (BDJ), the US National Science Foundation (CAS-MNP-2202621; CPW), The Seaver Institute (CPW and CMR), and The March Marine Initiative (a program of March Limited, Bermuda) through WHOI's Marine Microplastics Innovation Accelerator program (MEH).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank Kara Lavender Law (Sea Education Association), Larry Schubert (Westlake Corporation), and colleagues at the Eastman Chemical Company for their input and valued discussions while preparing this work.

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