Designing circular, sustainable, and non-persistent consumer plastic products: a case study of drinking straws

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ABSTRACT

Drinking straws present a simple form factor for evaluating material design strategies taken by manufacturers to achieve circular, sustainable, and non-persistent products in response to global restrictions and consumer sentiment. We investigated thirteen on-the-market drinking straws of varying formulations, characterizing their physical, chemical, and marine biodegradation properties. These data informed sustainability metrics used for evaluating the effectiveness and tradeoffs of design strategies, ultimately arriving at four key conclusions. First, diverting anthropogenic methane as a renewable feedstock to make polyhydroxyalkanoates (PHA) resulted in the only straw with a net-negative global warming potential. Second, adding biogenic fillers to conventional polymers (e.g., polypropylene) to minimize plastic usage is unlikely to produce substantial environmental benefits compared to using alternative polymers. Third, many marketing claims about circularity, sustainability, and persistence were unsupported, likely magnifying the mismanagement and environmental impacts of these products. Fourth, improper disposal of compostable straws in landfills could increase the global warming potential of the item by up to six times and offset numerous advantages afforded by biodegradable materials, thereby warranting greater investment in waste management infrastructure. The analysis of design strategies and their tradeoffs provided herein should be applied broadly when developing and adopting future consumer products.

SYNOPSIS

Commercially viable and scalable strategies for achieving circular, sustainable, and non-persistent products and their tradeoffs were identified for designing future plastic products.

INTRODUCTION

Drinking straws are polarizing, frequently littered, and pervasive single-use products. Upwards of 50 billion drinking straws are used annually in the U.S.,[1] and because these products are improperly disposed of (mismanaged), they contribute to ~5% of coastal plastic debris globally.[2] To curb their deleterious impacts as pollution, regulations have targeted drinking straws globally from the municipal to federal levels, banning products perceived as persistent in the environment. In response to these restrictions and consumer sentiment, a market for more sustainable and less persistent drinking straws emerged. In recent years, the market has ballooned to include dozens of brands (**Table S1**) claiming to be less impactful to the environment. Such claims are predicated on the switch to plastic formulations using different polymers, such as polyhydroxyalkanoates (PHAs), and additives, such as organic and inorganic fillers.

Environmentally conscious consumers, businesses, and policymakers face challenges navigating advertising for these new drinking straws.[3] The details provided by brands and manufacturers range from cryptic and vacuous marketing language to informative and readily accessible messaging. This fact is belabored by the myriad certifications and labels on product packaging that require a detailed understanding of their test methods to fully appreciate the nuances and reasonable claims that can be drawn from them. Two of the most frequently used labels are from certifiers Tüv Austria and the Biodegradable Products Institute (BPI),[4,5] which provide certificates for home and industrial compostability. These third parties certify polymer resins and products according to compostability standards (e.g., ASTM 6400[6]), as well as their additional scrutiny. Other labels reflect claims of feedstock renewability and global warming potential (GWP). The emphasis on certification is a legal matter (e.g., under the U.S. Federal Trade Commission Act[7]).

Certification is necessary for businesses to substantiate any environmental marketing claims, particularly those related to degradability.

Addressing persistence has often been met by designing straws for degradation in engineered environments, such as compost. This attribute is necessary for circular material schemes following a managed life cycle. Yet, the safeguard solution to the pollution of frequently mismanaged items is to imbue the items with inherent degradability in all environments: engineered and natural.[8] This feature has been advocated as one of six key interventions for mitigating the potential impacts of plastic pollution by embracing the principles of green chemistry and engineering in material and product design.[9–11]

While many drinking straws are certified as compostable and claim biodegradability, few present evidence for their degradation in the marine environment, where these items are ubiquitous.[12] Many compostable polymers feature incongruent degradation behavior with natural environments (e.g., polylactic acid, PLA).[13–15] Additionally, while certificates for marine biodegradability exist, the methods for evaluating marine degradation do not represent natural conditions because of well-recognized bottle effects.[13] In short, these methods provide evidence that marine microbes can biodegrade a material, but they are incapable of estimating lifetimes in natural settings. Having intrinsic biodegradability in the marine environment is necessary for plastic products, such as drinking straws, that frequently leak into the ocean.[8]

Plastic pollution is not the only environmental impact drinking straw manufacturers have aimed to avoid and reduce by switching to alternative plastic formulations. Impacts across the entire life cycle are being addressed to varying extents. The approaches manufacturers take to reduce the life cycle environmental impacts of drinking straws represent a microcosm of the broader landscape of approaches tried by the plastics industry to address the impacts of feedstock and

end-of-life (EoL) disposal. Thus, drinking straws present a simple form factor (a hollow cylinder) invariant across brands for quantifying the environmental impacts of different commercially-viable material design strategies applied at scale for achieving sustainable plastic products.

Herein, drinking straws of varying formulations from different manufacturers were investigated for their environmental impacts. These straws encompass products manufactured by startups to multinational corporations being adopted by local stores and international brands alike. The straws were evaluated for their physical, chemical, and realistic marine biodegradation properties (i.e., lifetimes and microbial community composition), which informed sustainability metrics related to renewability, material efficiency, resource utilization, GWP, and environmental persistence. This analysis identified successful design strategies for sustainability and circularity, as well as their tradeoffs that should be applied broadly in designing future plastic products.

MATERIALS AND METHODS

Materials

The drinking straws used in this study included three PHA-based straws produced by Aircarbon, LifeMade, and Pura Vida Bioplastic, one calcium carbonate-filled straw made with an undisclosed resin produced by Strawfish, one agave bagasse-filled straw made with an undisclosed resin and produced by the Sustainable Agave Company, and two straws made from proprietary or undisclosed resins produced by Matter and LOLIWARE. An uncoated paper straw and a conventional polypropylene (PP) straw were used as representative biodegrading (positive control) and non-biodegrading (negative control) straws, respectively. The Aircarbon, LifeMade, and Pura Vida Bioplastic straws were labeled PHA1, PHA2, and PHA3. The Strawfish and Sustainable Agave Company straws were labeled "$CaCO_3$ filled Resin" and "Agave Bagasse filled

Resin". The Matter and LOLIWARE straws were labeled Resin 1 and Resin 2. The positive and negative control straws were labeled Paper and PP. The straws were characterized to have sufficient information for comparison and calculating sustainability metrics (**Supporting Information**). Details (**Section S1**) and findings (**Table S2**) on four additional drinking straws previously investigated by our group were included in the analyses for broader coverage of the design space.[14] These straws include a cellulose diacetate (CDA) straw provided by Eastman, two PHA straws produced by Phade and Beyond Green (labeled PHA 4 and PHA 5, respectively), and a PLA straw produced by Plasticless (labeled PLA).

Evaluation of marine biodegradation

The biodegradation of drinking straws under coastal marine conditions was assessed by three orthogonal and previously reported methods: short-term seawater incubations measuring microbial respiration,[16,17] long-term incubations in a continuous flow natural seawater mesocosm monitoring mass loss,[14–16,18–20] and analysis of microbial community composition.[14,18] The specific details of each approach are provided in the **Supporting Information**, **Tables S3-S4**, and **Figures S1-S6**.

Sustainability metrics

Several sustainability metrics were calculated, including renewability, material efficiency, embodied greenhouse gas (GHG) emissions, embodied water usage, projected environmental lifetime in the marine environment, and managed EoL GWP. Data were collated from literature sources for material properties not measured or calculated in this study (**Table S5**). The specific embodied GHG emissions for the biogenic filler materials ($CaCO_3$ and agave bagasse) were assumed to be negligible, i.e., they were assumed to be 100% sequestering. Material efficiency

was taken as the average mass of each straw. Embodied GHG emissions and embodied water usage were calculated as the product of the mass of each straw and the specific embodied GHG emissions and the specific water usage for its polymer and filler, respectively. Renewability was calculated as the fraction of renewable material used in each straw. Managed EoL GWPs were calculated for compost and landfill environments. For calculations, the Agave Bagasse filled Resin was assumed to be 25% agave bagasse. The Resin 1 straw was assumed to be a commercial blend of PLA and polybutylene adipate terephthalate (PBAT), consisting of 45% PLA and 55% PBAT. PBAT was assumed to be fossil-based.[21,22] Metrics were not calculated for the Resin 2 straw because of a lack of reliable data for this material and its exact composition.

Embodied GHG potential of biogenic materials. The embodied GHG potential of the biogenic materials used in the straws was estimated, assuming all the C associated with the material removed atmospheric carbon dioxide (CO_2). Embodied GHG potential was calculated according to **Equation 1**, where χ_C is the weight percent of C in the material (kg C/kg material), $\frac{n_{CO_2}}{n_C}$ is the stoichiometric ratio of CO_2 converted to carbon in the biogenic material (assumed 1), w_C is the molar mass of carbon (12 g/mol), and w_{CO_2} is the molar mass of CO_2 (44 g/mol).

$$C_{biogenic\ material} = (\chi_C)\left(\frac{n_{CO_2}}{n_C}\right)\left(\frac{w_{CO_2}}{w_C}\right) \quad (1)$$

The values of χ_C were retrieved from reported values in the peer-reviewed literature. Calcium carbonate is 12 wt% C, and agave bagasse has been reported to be 41.25 wt% C.[23]

EoL GWP. The EoL GWP of a biodegradable material was estimated for landfill and composting environments. Only contributions from methane (CH_4) and CO_2 were included in the estimates. The Buswell equation[24] was used for landfill conditions to estimate the stoichiometric ratios for

converting the biodegradable material to CH_4 and CO_2. For composting conditions (aerobic conditions), all the carbon in the material was assumed to be converted to CO_2. The GHG potential was calculated as the sum of the contributions from CH_4 and CO_2 in units of CO_2-eq/kg material. The specific EoL GWP for the materials was calculated using **Equation 2**, where GWP_{CO_2} is the 100-year global warming potential of CO_2 equal to 1 kg CO_2-eq/kg CO_2, GWP_{CH_4} is the 100-year global warming potential of CH_4 equal to 28 kg CO_2-eq/kg CH_4, $\frac{n_{CO_2}}{n_C}$ is the stoichiometric ratio of carbon converted to CO_2 (assumed 1 for compost and calculated for the material using the Buswell equation for landfill), $\frac{n_{CH_4}}{n_C}$ is the stoichiometric ratio of carbon converted to CH_4 (assumed 0 for compost and calculated for the material using the Buswell equation for landfill), and w_{CH_4} is the molar mass of CH_4 (16 g/mol).

$$C_{GWP}^{EoL} = \left(GWP_{CO_2}\right)(\chi_C)\left(\frac{n_{CO_2}}{n_C}\right)\left(\frac{w_{CO_2}}{w_C}\right) + \left(GWP_{CH_4}\right)(\chi_C)\left(\frac{n_{CH_4}}{n_C}\right)\left(\frac{w_{CH_4}}{w_C}\right) \quad (2)$$

The calculations for each straw material are provided in the **Supporting Information**.

Social costs

The social costs for the associated GHG emissions due to the straws were calculated according to **Equation 3**,

$$V_{GHG} = \alpha_{GHG} C_{GHG} m_0 \quad (3)$$

where V_{GHG} is the social cost of GHG emissions for the straw, α_{GHG} is the exchange constant for GHG emissions, C_{GHG} is the specific GHG emissions for the material, and m_0 is the initial mass

of the straw. GHG emissions included CO_2 and CH_4; a 50% capture efficiency for landfill CH_4 emissions was assumed.[25] The social costs related to the marine plastic pollution of the straws were calculated following our previously reported method[26] and using **Equation 4**,

$$V_P = \alpha_P \chi_P f_P m_0 t_L \left(\frac{3l_0 - h_0}{6l_0}\right) \quad (4)$$

where V_P is the social cost of marine plastic pollution for the straw, α_P is the exchange constant for marine plastic pollution, χ_P is the total fraction of plastic leaking into the ocean (0.11), f_P is the fraction with which drinking straws contribute to the total amount of leaked plastic (0.05), t_L is the projected lifetime of the straw, l_0 is the initial length of the straw, and h_0 is the initial thickness of the straw.[2,27] The social cost calculation was adjusted by χ_P and f_P because not every item leaks into the environment.[28] All dollar values are presented in 2024 U.S. dollars (US$).

RESULTS

Evaluating the potential environmental impacts of drinking straws requires knowing what material(s) were used to make the straws and the dimensions and properties of the straws. This data was collected by reviewing product marketing, regulatory, and third-party certification documents and databases, as well as characterizing the thickness, mass, density, and composition of the straws. Overall, the available information about the straws varied considerably between brands. Paper straws were generally promoted as biodegradable and compostable, often without emphasis on certifications. As for PP straws, marketing materials made little to no mention of sustainability. Despite their differences, the unit price of each straw in 2023 dollars, when purchased in bulk, ranged from 0.02 to 0.08 US$/straw. The properties of each straw are summarized in **Table 1**.

PHA1

According to the manufacturer's website, product packaging, and regulatory documents,[29,30] the PHA1 straw was made of a poly(3-hydroxybutyrate) (P3HB) produced by Newlight Technologies and met several third-party biodegradation certification standards for compostability (Tüv Austria Home and Industrial S2100; BPI Certified).[31,32] To meet the standards, the certifying bodies prescribed a maximum nominal thickness for the straws of 152 μm (Tüv) and 182 μm (Tüv, BPI), depending on the material and standard. Additionally, promotional materials from the manufacturer labeled the straws as carbon-negative, sequestering 52.5 g CO_2-eq/straw (119.9 kg CO_2-eq/kg material) as verified by SCS Global Services following ISO 14044:2006 for manufacturing and disposal.[33] Carbon sequestration resulted from the use of diverted anthropogenic CH_4 emissions as its feedstock.[34] Analysis of the stable and radiocarbon isotopic composition for the straw confirmed a fossil-derived methanogenic C source ($\Delta^{14}C$ = -1000 ± 0.2‰, $\delta^{13}C$ = -42.3 ± 0.1‰, n = 3).

PHA2

The packaging of the PHA2 straw stated it was made from a PHA material with the tradename Nodax, produced by Danimer Scientific. In March 2025, Danimer Scientific filed for bankruptcy.[35] Regulatory documents disclosed that the food-contact approved grade of these materials is a random copolymer in which 3-hydroxybutyrate units represent approximately 75% of the polymer, with 3-hydroxyvalerate, 3-hydroxyhexanoate, 3-hydroxyoctanoate, and/or 3-hydroxydecanoate monomer units representing up to 25% of the polymer.[36] Nodax PHAs are certified bio-based (Tüv Austria S0292), using vegetable oils as renewable feedstocks.[32,37] The straws met several third-

party biodegradation standards for compostability (Tüv Austria Home S2594; BPI Certified).[31,32] To meet the standards, the certifying bodies prescribed a maximum nominal thickness for the straws of 190 µm (Tüv) and 203.2 µm (BPI). While not advertised, it had a measurable inorganic additive content of 15.9 wt%. The infrared (IR) spectrum of PHA2 reflected that of a PHA and included characteristic peaks for $CaCO_3$, indicating that its inorganic additive content was most likely $CaCO_3$ (**Figure S7**). Of Tüv Austria certified home compostable drinking straws, Nodax was one of the most common materials used by different brands (e.g., LifeMade S2594, Biolo S2166, Phade S1328, Eagle Beverage S2332, Urthpact S0589, Greenprint S2380).[32]

PHA3

According to promotional documents and social media posts,[38,39] the PHA3 straw was made of a polyhydroxybutyrate-hexanoate (PHBH) produced by Kaneka Green Planet.[40] Regulatory documents disclosed that the food-contact grade of the material is poly(3-hydroxybutyrate-co-3-hydroxyhexanoate).[41] The straws were labeled a U.S. Department of Agriculture (USDA) Certified 100% bio-based product and certified bio-based (Tüv Austria S0318), using vegetable oils as renewable feedstocks.[38] The straws met several third-party biodegradation standards for compostability (Tüv Austria Home and Industrial S2541; BPI Certified).[31,32] To meet the standards, the certifying bodies prescribed a maximum nominal thickness for the straws of 185 µm (BPI) and 320 µm (Tüv). The measured thickness was greater than the specified limit for BPI certification (**Table 1**).[38]

Filled resins

According to the manufacturer's website and promotional materials,[42] the $CaCO_3$ filled Resin straws were made with a resin filled with calcium carbonate and unspecified enzymatic

degradation additives.[43] The calcium carbonate was derived from waste oyster shells sourced from Mexico. Marketing materials claimed the straws could biodegrade in 12-18 months in natural landfills (ASTM D5526[44]) and outdoor conditions through aerobic and anaerobic processes.[43] According to the manufacturer's website,[45] the Agave Bagasse filled Resin straws were made with material from the agave plant unused in tequila production and were biodegradable.[46] The formulated resin was claimed to have a lifetime of 10-24 months in soil.[47] The manufacturers of the $CaCO_3$ filled- and Agave Bagasse filled- Resin straws did not disclose the polymer used to make their straws in marketing materials. The IR spectra for the $CaCO_3$ filled Resin and the Agave Bagasse filled Resin straws matched that of PP (**Figures S8-S9**). Along with the characteristic peaks for PP, the IR spectrum of the $CaCO_3$ filled Resin straw included well-defined peaks for $CaCO_3$ at 1450, 1420, and 874 cm^{-1}. The measured inorganic additive content was 17.8 ± 0.1 wt% (n = 3), presumably all $CaCO_3$.

Resin 1

Product packaging for the Resin 1 straw indicated it was made from NatureStar resin, advertised as a biodegradable and compostable biopolymer.[48,49] The product website stated that "straws will breakdown within 12 months, leaving only biomass behind which can be used to enhance soil".[50] The straw met several third-party biodegradation standards for compostability (Tüv Austria Home S2699; BPI Certified).[31,32] In conflict with the certifications, the product page on the retailer's website stated that the straw is only commercially compostable.[49] To meet the standards, the certifying bodies prescribed a maximum nominal thickness for the straws of 246 μm (BPI) and 190 μm (Tüv). The measured thickness was greater than the specified limit for Tüv certification (**Table 1**). The polymer used in the NatureStar resin was undisclosed. The IR spectrum for the Resin 1 straw suggested it was a PLA/PBAT blend, displaying peaks for both polymers (**Figure**

S10).[51,52] The IR spectrum of the Resin 1 straw included characteristic peaks for PLA at 1754 and 757 cm^{-1} and for PBAT at 1712, 1169, 1121, and 725 cm^{-1}.

Resin 2

According to marketing materials and the product website,[53] the Resin 2 straw was made from SeaTech resin, a seaweed-derived bio-polymer blend compounded with "shell powder" and "mineral color". More descript details on the material were disclosed in published patents,[14,54] wherein the formulated resin can be composed of at least kappa-carrageenan, chitosan, glycerol, calcium carbonate, and water. The measured inorganic additive content was 30.8 $\pm$ 0.1 wt% (n = 3), and elemental analysis by X-ray fluorescence (XRD) of the inorganic material detected K, Ca, Co, and Cr. The IR spectrum of the inorganic material included peaks for $CaCO_3$, as well as several others. Presumably, some of these additional IR peaks and the Co and Cr detected by XRD belong to the blue mineral-based colorant (possibly cobalt chromite blue). The potassium likely came from K_2CO_3, as it is mentioned as a possible component in a published patent, and no other elements were detected by XRD as possible anions.

Table 1. Drinking straw properties

Straw	Unit Price [US$/straw][a]	Polymer	Filler	Mass [mg][b]	Thickness [mm][c]	Density [g/cm^3][c]	Inorganic Content [wt%][d]
Paper	0.03	Paper	None reported	1133.0±8.2	0.33±0.02	0.75±0.02	ND
PHA1	0.05	P3HB	None reported	437.8±13.4	0.12±0.01	1.37±0.03	ND
PHA2	0.08	PHA copolymer	None reported	953.2±29.2	0.19±0.01	1.41±0.03	15.9
PHA3	0.03	PHBH	None reported	863.1±32.2	0.25±0.01	1.13±0.05	ND
Resin 1	0.05	PLA/PBAT blend	None reported	1028.0±11.0	0.23±0.01	1.22±0.02	ND
Resin 2	0.08	Seaweed-based biopolymer blend	$CaCO_3$	2117.0±90.4	0.49±0.05	1.30±0.14	30.8
$CaCO_3$ filled Resin	0.02	PP	$CaCO_3$	745.7±12.3	0.25±0.02	1.03±0.01	17.8
Agave Bagasse filled Resin	0.04	PP	Agave bagasse	816.9±10.1	0.29±0.04	0.85±0.01	ND
PP	0.03	PP	None reported	614.5±1.7	0.15±0.01	0.91±0.02	ND

[a]In 2023 US$ for bulk purchasing
[b]Presented as the mean ± standard deviation of five measurements for the product
[c]Presented as the mean ± standard deviation of seven to eleven measurements
[d]Presented as the mean of one to three measurements; ND = not detected

Biodegradation under coastal marine conditions

To establish the potential for marine biodegradation, oxygen respiration of the microbes associated with the straws was assayed. Respiration rates greater than the seawater-only baseline provide evidence that the associated microbes can biodegrade the straws. These short-term bottle incubations over three weeks showed that the PHA1-3, Resin 1, and paper straws stimulated microbial respiration to varying degrees above the baseline (**Table S6**), supporting marine biodegradability. The Resin 1 and paper straws had comparable respiration rates, about double those of the PHA1-3 straws. The PP-based straws (PP, $CaCO_3$ filled Resin, and Agave Bagasse filled Resin straws) had respiration rates comparable to seawater, discounting their marine biodegradability. The Resin 2 straw was unable to be assayed due to complications with the poisoning agent (**Section S2**).

While short-term bottle incubations help establish whether microbes can degrade a polymer, open mesocosm systems provide more environmentally relevant evidence for microbial degradation of a polymer over other available carbon sources in coastal settings (e.g., natural organic matter). Thus, we incubated the straws for 30 weeks in a continuous flow seawater mesocosm to assess the mass loss rates of the straws under coastal seawater conditions. All the straws developed appreciable biofilms throughout the incubation (**Figure 1A**). By 30 weeks, the PHA straws lost 30-50% of their mass, the paper straw lost ~70%, and the Resin 1 straw lost ~10% (**Figure 1B-C**). The PP-based straws showed no mass loss (**Figure 1C**). Having established the potential for the biodegradability of several straws and that our mesocosm is without mechanical action and sunlight to cause fragmentation, any mass loss was attributed to biodegradation.

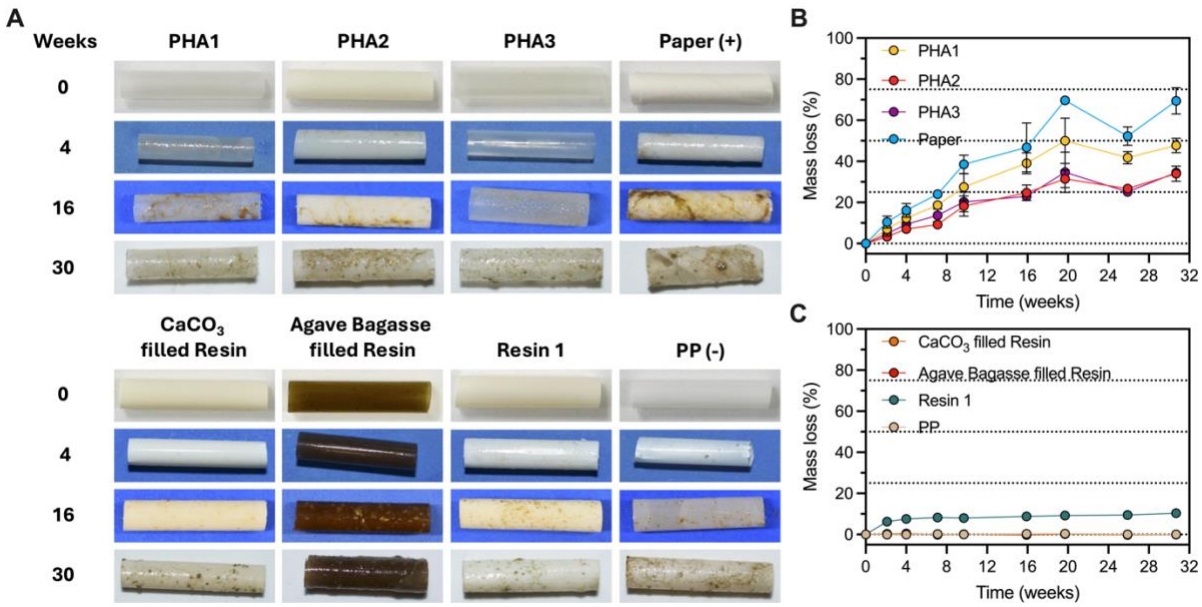


Figure 1. Representative images of each straw initially and after 4, 16, and 30 weeks in a flow-through seawater mesocosm (**A**). Relative mass loss of the PHA and paper straws (**B**) and the PP-based and Resin 1 straws (**C**) Data are presented as the mean ± standard deviation of three replicates unless otherwise noted (**Table S4**).

In contrast to the agreement between microbial respiration and mass loss for the PHA, paper, and PP straws, the Resin 1 straw displayed unique behavior (**Figure 1C**, **Table S6**). The Resin 1 straw had a relatively large amount of mass loss at the first time point, followed by a much slower mass loss rate for the remainder of the incubation (**Figure 1C**). This behavior is likely from the rapid leaching of a biodegradable additive,[14,15] consistent with the large oxygen respiration rate for the straw measured in the short-term respiration experiments.

The Resin 2 straw broke apart in the mesocosm and developed a paste-like consistency, preventing an assessment of its mass loss. When incubated in the mesocosm, the straw broke apart and accumulated at the bottom of the tank within 8 weeks (**Figure S11**). Over the next 30 weeks, there was little visual change in the amount of the Resin 2 material that settled to the

bottom (**Figure S11**). Presumably, the material that collected at the bottom of the tank and persisted was the inorganic material that made up the Resin 2 straw, as it retained its blue color.

Assessing microbial community composition provides an orthogonal measure of biodegradation. Beta diversity analysis by Bray–Curtis dissimilarity indicated distinct community compositions in response to the different materials (PERMANOVA, $p<0.01$) (**Figure 2**), suggesting the degradability (**Figure 1**) and material properties of the straws selected for distinct microbial communities. The straws that degraded had unique microbial communities, differentiating by the type of material. In contrast, the three PP-based straws had similar community structures and were separate from those of the degradable straws and seawater. This result suggests that these straw materials mainly provided surfaces for the colonization of microorganisms rather than substrates for metabolism, an observation consistent with our previous findings.[18] Microbial community composition analysis at the family level revealed detailed differences between the PHA, PP-based, Resin 1, paper straws, and seawater (**Figure S12**; **Section S3**), paving the way for future investigations to delve into the details of specific microbial species and functions underlying plastic biodegradation in the ocean.

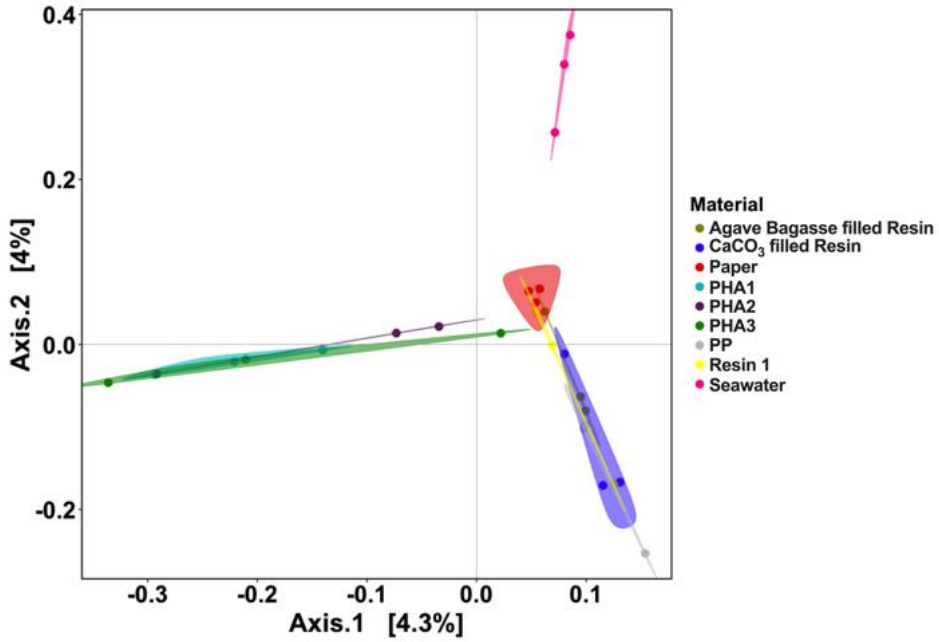


Figure 2. Beta diversity of microbial communities based on Bray–Curtis dissimilarity of 16S rRNA gene sequences visualized by principal coordinates analysis.

Estimated environmental lifetimes under coastal marine conditions

The mass loss data were fit to a phenomenological surface erosion model to derive the specific surface degradation rate (k_d) of the straw materials. This material property quantifies the rate of surface erosion of a material in a given environment, accounting for the effects of material properties and environmental conditions. The values of k_d for the PHA straws were 50±6 μm/year for PHA1, 54±5 μm/year for PHA2, and 66±8 μm/year for PHA3. Though minor, the differences in the values of k_d for the PHA straws suggested an effect of the polymer, which should be investigated further to understand the influence of PHA copolymer composition on degradation rates. The values of k_d for the paper and Resin 1 straws were 190±18 μm/year and 7±0.6 μm/year, respectively. The values of k_d for the PP-based straws were constrained to less than 0.5 μm/year.

With the values of thickness and k_d, the projected environmental lifetimes of the straws were calculated. The paper straw had the shortest projected environmental lifetime of 11±1 months. Values of projected environmental lifetime for the PHA straws were 15±2 months for PHA1, 21±2 months for PHA2, and 23±3 months for PHA3. The Resin 1 straw had a projected lifetime of 197±20 months. The projected environmental lifetimes for the PP-based straws were constrained to a minimum of 1800 months. No environmental lifetime was projected for the Resin 2 straw.

DISCUSSION

Drinking straws reflect the broader challenges to create products that i) work as intended, ii) meet consumer preferences, iii) are inexpensive, and *now* iv) satisfy circularity, sustainability, and degradability goals. Achieving these objectives for a drinking straw, an arguably simple product is not so simple, as evidenced by the different straws investigated in this study. Each product satisfies these four criteria to varying degrees and via different approaches. For the first three criteria, each straw works as intended, meets consumer preferences, and is inexpensive to differing extents (**Section S4**).

To satisfy circularity, sustainability, and degradability goals, each straw approached them through different combinations of feedstock, plastic formulation, and EoL management. All but the Resin 2 straw was included in this analysis because of a lack of reliable data for this material. Nonetheless, a brief general discussion on the sustainability of seaweed-based materials is presented in **Section S5**. Additionally, the straws investigated in our previous study[14] (CDA, PLA, PHA4, and PHA5, see **Section S1**) were included to reflect the broader design space of drinking straws.

Feedstock renewability

To fit into a circular economy framework, a renewable feedstock is one in which the carbon has been recirculated, including carbon obtained from biomass, industrial by-products, waste CO_2 or CH_4, or recycled plastics.[55] Most straws were made from 100% renewable materials (**Figure 3A**). Only those with fossil-based polymers (i.e., PP and Resin 1) were partially or entirely made from non-renewable materials.

The investigated PP-based straws appear to use comparable amounts of polymer to that of a pure PP straw, negating the otherwise would be benefit of the renewably sourced filler. PP is primarily produced using non-renewable petroleum sources, and ~5.5% is recycled. Biogenic fillers (i.e., oyster-derived $CaCO_3$ and agave-derived bagasse) can reduce the total amount of polymer by replacing it with a renewable material. For instance, the $CaCO_3$ filled Resin had an average mass of ~746 mg, being ~18 wt% $CaCO_3$ meant that ~612 mg of the straw was PP, effectively the same amount of material as the pure PP straw (~615 mg).

PHAs are produced by fermentation, using various carbon sources as feedstocks.[56] The PHA used in the PHA1 straw uses CH_4 diverted from anthropogenic sources (e.g., wastewater, cattle farming, landfills, and coal mining) as the carbon source, yielding a carbon offsetting material. In contrast, the PHA2-5 straws use agricultural products, such as vegetable oils, to produce their PHA materials. PHA2 was not 100% renewable because of its fraction of $CaCO_3$ of unknown origin (assumed non-biogenic).

Similar to PHAs, PLA is synthesized using lactic acid produced by the fermentation of agricultural products.[57] Therefore, PHAs and PLA made using these feedstocks can be certified as 100% bio-

based. The Resin 1 straw was determined to be a blend of PLA and PBAT, and so was partially bio-based, owing to its PLA content. PBAT is predominantly fossil-based, but efforts are being made to circularize its feedstocks to include those from recycled materials and bio-based sources.

Historically, CDA has been a mixed feedstock wherein the cellulose was bio-derived, and the carbon within the acetyl modification was derived from coal. Recognizing the non-renewability of coal as a carbon source, more sustainable grades of CDA are being produced by deriving the acetyl C from molecularly recycled mixed waste.[58]

Material efficiency

Material efficiency quantifies the amount of material used to make a functional product.[59] Optimizing the material efficiency of a plastic product has the added benefit of reducing many other environmental impacts (e.g., GHG emissions and freshwater usage) because these impacts are largely proportional to the amount of material used.[60–62] Material efficiency also affects environmental impacts related to shipping because fuel efficiency decreases with increasing cargo weight by a nontrivial amount.[59,63] Because all the straws have the same function, their mass is a measure of their material efficiency. The PHA1 straw had the greatest material efficiency, followed by the PP straw (**Figure 3B**). The PHA1 straw used ~33% less material than the PP straw. The other PHA and PP-based straws were less materially efficient, using more material to produce a functional product. The paper straw was one of the least efficient, requiring ~60% more material than the PP straw.

Embodied GHG Emissions

A first estimate for the GHG emissions of a product are the emissions associated with the production of its materials. Because the specific embodied GHG emissions of plastics are within an order of magnitude of each other, as were the masses of each straw, differences in GHG emissions between products were expected to be marginal.[26] This was not the case.

PHA1 was the only straw with net-negative embodied GHG emissions (**Figure 3C**), owing to diverted CH_4 emissions as its feedstock. Scaling this approach could impact the global C cycle and climate change. For instance, if all the C used in plastic packaging globally (~142 Mt/yr[64]) were P3HB (~56 wt% C) and came from anthropogenic CH_4, then ~71 Mt CH_4 (~2.2 Gt CO_2-eq) would be needed. Adopting this strategy would offset ~20% of the ~9.7 Gt CO_2-eq of annual global anthropogenic CH_4 emissions.[65] Conversely, the other straws were all carbon-positive, ranging from 0.80 kg CO_2-eq/1000 straws for the paper to 4.16 kg CO_2-eq/1000 straws for the Resin1, PLA/PBAT-based straw (**Figure 3C**).

Relative to selecting materials with more renewable feedstocks, the effectiveness of biogenic fillers appears negligible. The theoretical maximum offset in GHG emissions for oyster-derived $CaCO_3$ is ~0.44 kg CO_2-eq/kg $CaCO_3$. In practice, this value is likely reduced as GHG emissions can be associated with the processing of the oyster shells to yield $CaCO_3$ of a quality suitable for compounding. Based on its formulation, the theoretical maximum reduction in embodied GHG emissions compared to the PP straw is only 4% for the $CaCO_3$ filled Resin straw. The value of the theoretical specific embodied GHG emissions for agave-derived bagasse is greater than oyster-derived $CaCO_3$, offsetting ~1.51 kg CO_2-eq/kg agave-derived bagasse. As with oyster-derived $CaCO_3$, this value is likely less because of GHG emissions associated with processing the material. While the amount of agave-derived bagasse used in the Agave Bagasse filled Resin straw was not disclosed, biocomposites of agave-derived bagasse and PP typically include 20-

30 wt% bagasse. Within this range, the estimated reduction in embodied GHG emissions for the Agave Bagasse filled Resin straw compared to the PP straw was 8 to 28%.

Water usage

An impact of growing concern is a material's embodied water usage because of the scarcity and diminishing quality of freshwater resources globally.[66,67] Generally, plastics derived from agricultural products have greater embodied water usage than petroleum-derived plastics, owing to the water used in agriculture and downstream processing. However, these impacts can be an order of magnitude less than those resulting from paper production. Paper and pulp mills pollute freshwater ecosystems and diminish their value, as well.[68] Reported values for the embodied water usage of PP, PHA, and paper are 32 L/kg, 240 L/kg, and 1700 L/kg, respectively.[69] Thus, while the paper straw can have some of the lowest embodied GHG emissions (~2-3 times less than the others, excluding PHA1), it can have substantial embodied water penalties (~10-80 times more than the others) (**Figure 3D**). Water is a valuable natural resource; thus, reducing its usage as much as possible will benefit society.[70,71]

EoL (mis)management and GWP

Managed EoL. The strategies advertised and promoted for the managed EoL of the straws varied with the material. The PP-based straws were intended to follow a linear EoL path with disposal in landfills. The PHA-based, paper, and Resin 2 straws were intended to follow a more circular EoL path with disposal in industrial or home composting systems. The Resin 1 straw was intended to be industrially composted.

Today, most managed plastic waste is landfilled,[72] some is incinerated, and even less is recycled and composted.[73] While PP is recyclable, PP straws are often not accepted by municipal recycling facilities because of their size and shape, and contamination from food. In the U.S., ~63% of municipal solid waste is landfilled.[74] In many instances, it is the only waste management option available.

The filled PP straws were claimed to biodegrade in landfills. The $CaCO_3$ filled Resin straw was advertised for disposal in landfills and to be formulated with an enzymatic package to support its biodegradation in that environment.[43] These additives are designed to stimulate enzymatic degradation of the polymer by fouling microbes under anaerobic conditions, though their effectiveness has been dubious.[75,76] Collectively, the respiration, mass loss, and microbial community composition analyses suggest these additives were not stimulating the biodegradation of the PP matrix in aerobic marine conditions. The Agave Bagasse filled Resin straw was advertised for "avoiding landfills" but did not mention where it was intended to go. Being PP, this straw likely could only be properly disposed of by landfilling or incineration. There is little evidence to support the possibility of either straw's biodegradation in landfills (i.e., no third-party certificates for the products). However, taken at face value, assuming the claims hold that the filled PP straws can biodegrade in terrestrial and landfill environments, their disposal in landfills would result in biogenic CH_4 emissions (**Figure 3E**). Landfills contribute ~10% of global anthropogenic CH_4 emissions, and their leachates can diminish fresh and groundwater resources.[77] Because of biogenic CH_4 emissions, promoting landfilling as the managed EoL strategy can have significant associated GHG emissions for all but the non-biodegradable straws (**Figure 3E**).

Composting can be an alternative EoL strategy. Unlike landfilling, composting is an aerobic microbial degradation process that converts organic matter to biomass and CO_2, not CH_4. As a result, the GWP of GHG emissions can be an order of magnitude less for compost than landfill

(**Figure 3E**). Composting can be operated on the industrial scale using elevated temperatures or at the individual scale using ambient conditions (i.e., home composting). Some materials are only certified industrially-compostable (e.g., PLA), while others are certified home-compostable (e.g., PBAT, PHA, and CDA). For food-soiled, single-use items, composting affords a strategy well-equipped to handle such waste alongside food scraps.

Nonetheless, composting has its challenges. Presently, composting is rarely practiced and lacks available infrastructure at the municipal level. In the U.S., it has been estimated that only ~4% of food waste is composted.[78] Thus, while products are meant for and designed to be composted, they may rarely follow that intended path and instead enter landfills or incinerators. Moreover, composting is not without its environmental impacts, as well. Improperly aerated compost can result in CH_4 emissions in the same way as landfills. For composting to be broadly adopted, it will require greater investment by consumers and communities in composting capabilities for biodegradable plastics.

Mismanaged EoL. Drinking straws can be mismanaged at their EoL by being littered or disposed of in the wrong waste stream (e.g., landfilled instead of composted). In the event of littering, several of the straws will persist in the coastal ocean despite claims of their degradability in other environments (e.g., compost or soil). The PP-based and Resin 1 straws were estimated to persist for decades or much longer if leaked (**Figure 3F**). Notably, the Resin 1 straw exhibited ~10% mass loss after 30 weeks of incubation (**Figure 1**). However, the microbial community structure was similar to that of the PP-based straws (**Figure 2**), which is unexpected if the community was adapting to metabolize PBAT. Considering this finding, further analyses of the Resin 1 material are necessary to confirm whether the shallow mass loss rate after the first time point was due to a residual additive slowly leaching, the slow metabolism of the polymer by fouling microbes, or other processes. Conversely, because the PHA- and CDA-based straws were shown to

biodegrade in the coastal ocean, they were estimated to last 1-2 years, slightly longer than paper. For the straws that were not persistent, their differences in estimated environmental lifetimes reflected tradeoffs in material and geometric properties.

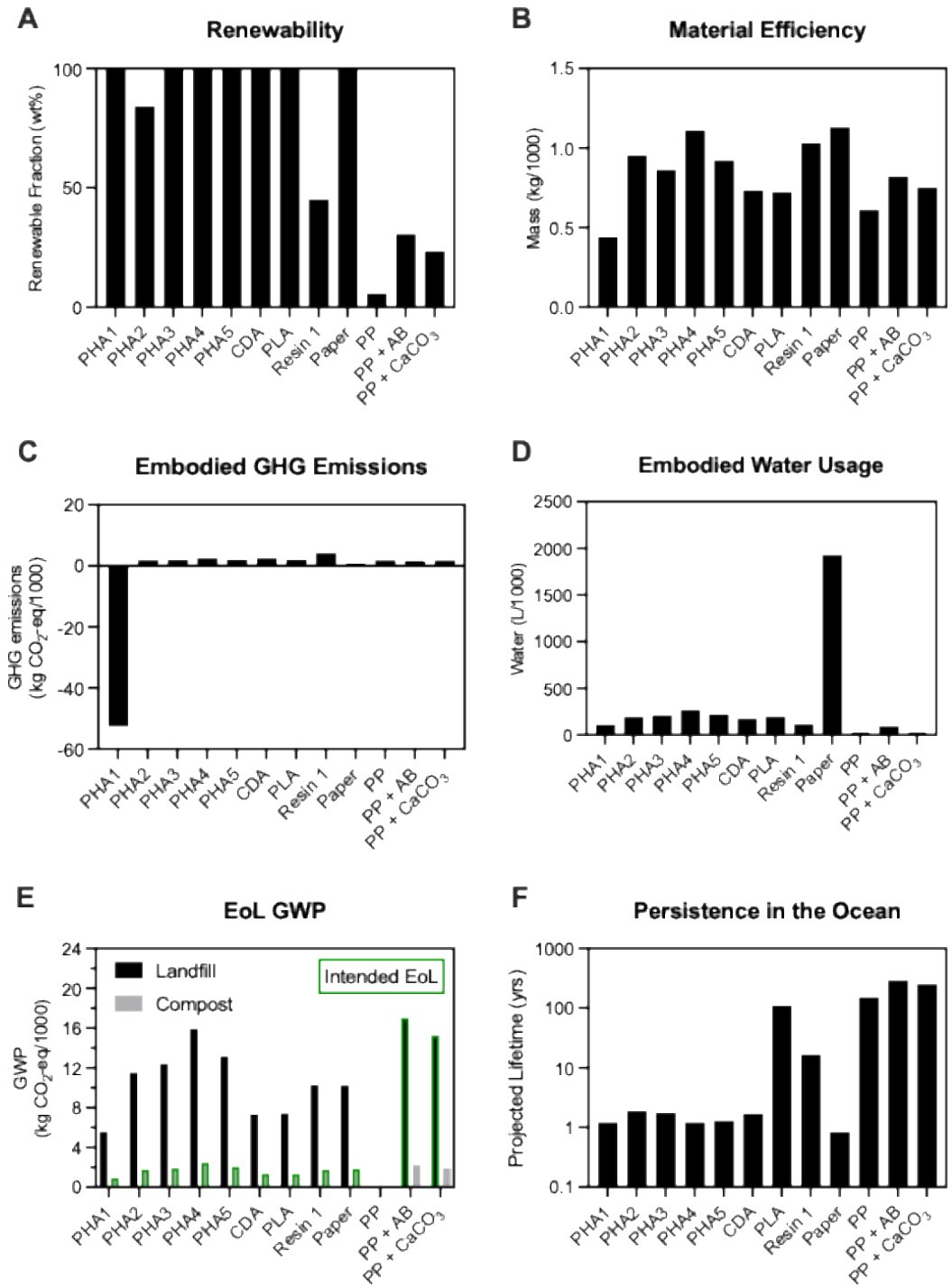
Disposal of drinking straws in landfills intended for compost results in additional and more potent GHG emissions that otherwise would not have been produced. This outcome is because anaerobic landfill conditions produce CH_4 during the biodegradation of the material that escapes collection. The added GWP from improper disposal of compostable materials in landfills was estimated to range from 4.64 to 13.44 kg CO_2-eq/1000 straws (**Figure 3E**), resulting in approximately six times more GWP per straw. The conventional PP straw, in contrast, has zero GWP in compost or landfills because of its presumed recalcitrance in landfills.

Social costs of GHG emissions and plastic pollution

Social costs were used to quantify, contextualize, and compare the environmental impacts of marine plastic pollution and GHG emissions. Social costs reflect the external costs to society associated with a good, service, or outcome. The exchange constant (the conversion factor of environmental impact to monetary value) for the social cost of marine plastic pollution was proposed to range between 4.58 to 45.8 US$/year kg plastic.[79] Using the lower value for a conservative estimate, switching from persistent to non-persistent plastics for drinking straws can equate to savings for society of ~3 $USD/1000 straws (**Table S7**). Scaled to the estimated number of straws that leak into the environment in the U.S. annually, the switch represents a potential savings of ~150 million US$/year.

Social costs were also quantified for GHG emissions associated with producing straws and improper disposal of compostable straws in landfills. The exchange constants for social costs of

589 CO_2 and CH_4 have been estimated to be 0.22 US$/kg CO_2 and 3.40 US$/kg CH_4, respectively.[80,81]
590 The social costs for the embodied GHG emissions of the straws (excluding PHA1) ranged from
591 0.18-0.92 US$/1000 straws and scaled to the annual consumption rate of drinking straws in the
592 U.S. could cost 9 to 46 million US$/year. PHA1 was unique because it had negative embodied
593 GHG emissions at the beginning of life from using diverted anthropogenic CH_4 as a feedstock. As
594 a result, it was estimated to equate to savings of 11.55 US$/1000 straws or ~578 million US$/year.
595 The social costs from the added GHG emissions due to landfilling a compostable drinking straw
596 ranged from ~0.21-0.61 US$/1000 straws (**Table S7**) and scaled to the estimated annual U.S.
597 drinking straw consumption rate, representing a potential burden of 11 to 31 million US$/year.
598
599 From this analysis, three key points emerged. First, conventional PP straws do not contribute to
600 societal costs in terms of GHG emissions at EoL regardless of whether they accumulate in
601 compost or landfill because they are non-biodegradable; however, they contribute sizably to
602 societal costs when littered in the marine environment for that same reason. Second, for PHA1,
603 the societal costs at EoL, regardless of the scenarios investigated, could be entirely offset by the
604 savings to society by using diverted CH_4 emissions as a feedstock to produce the polymer. Lastly,
605 the societal costs from the improper disposal of compostable and marine-biodegradable straws
606 (i.e., paper, PHA, and CDA) in landfills were estimated to be 18-36 times greater than those from
607 their improper disposal as marine litter (**Table S7**). While this analysis only discusses the social
608 costs of two environmental impacts (plastic pollution and GHG emissions), of which there are
609 several others (e.g., resource utilization and eutrophication), it was instructive for contextualizing
610 the relative burden of the different drinking straws at EoL.



611

612 **Figure 3.** Comparison of sustainability metrics: renewability (**A**), material efficiency (**B**), embodied

613 GHG emissions (**C**), embodied water usage (**D**), EoL GWP (**E**), and persistence in the ocean (**F**).

614 The Agave Bagasse filled Resin and the $CaCO_3$ filled Resin are abbreviated PP + AB and PP +

615 $CaCO_3$, respectively.

Implications

From this case study of drinking straws, four valuable lessons were learned. First, the combination of approaches taken by the PHA1 straw resulted in a product that qualitatively and quantitatively could be the least impactful. It fits within a circular materials framework, had the greatest material efficiency, was non-persistent in the coastal ocean, and was carbon-offsetting by utilizing diverted anthropogenic CH_4 emissions as a feedstock. These design decisions are a promising set that could be adopted for other materials and products. Second, inorganic fillers can offset GHG at EoL, and biogenic wastes can be repurposed as fillers into new products, sequestering carbon as well. However, merely adding fillers to the status quo polymer (e.g., PP) will likely not produce significant benefits for the environment compared to using an alternative polymer. Third, many of the claims made by brands about circularity had limited supporting data, which likely will lead to the mismanagement of their products and unreliable outcomes. Thus, additional certifications are needed to give credibility to life cycle claims and the impacts that can result from different life cycle scenarios. Lastly, improper disposal of compostable products in landfills can have sizable environmental impacts, thereby warranting greater investment in infrastructure to manage compostable plastics and associated food waste properly. Otherwise, many of the advantages afforded by these materials will be nullified. Moving forward, from our analysis, consumers, brands, and policymakers should support products that divert anthropogenic GHGs for use as renewable feedstocks, promote the design of products for material efficiency and minimal persistence, and bolster proper disposal of compostable products by enhancing consumer education and supporting investment in industrial and home composting facilities.

ASSOCIATED CONTENT

Supporting Information

The following files are available free of charge.

Extended materials and methods; details of previously investigated drinking straws (Section S1); interference by the poisoning agent (Section S2); microbial community composition analysis at the family level (Section S3); discussion of non-sustainability-related design considerations for drinking straws (Section S4); discussion of the sustainability of seaweed-based materials (Section S5); plots of relative mass loss data for each straw with curve fit (Figure S1); random samplings of straw thickness, k_d, and projected environmental lifetimes (Figures S2-S6); IR spectra of select drinking straws (Figures S7-S10); photos of Resin 2 in the mesocosm (Figure S11); microbial community compositions at the family level (Figure S12); list of drinking straws on the market (Table S1); properties of previously investigated drinking straws (Table S2); mass loss data (Table S3); relative mass loss data (Table S4); global warming and resource utilization properties (Table S5); short-term microbial respiration rates (Table S6); calculated social costs (Table S7); additional references (PDF).

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Notes

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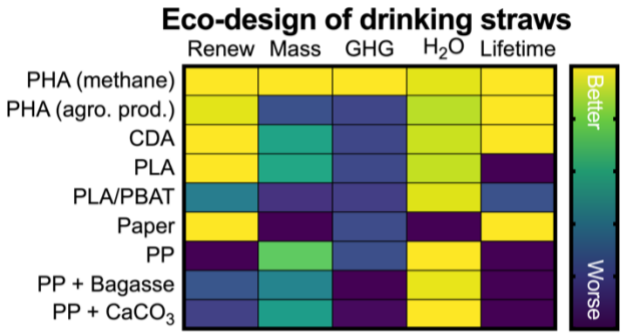

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