

Evaluation of Microplastics Environmental Impact from Straws in the US over Time: Scenario Based Semi Quantitative Scaling Emission Approximation Versus Bioresin Alternatives to Polypropylene

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Abstract

Microplastics pollution has been analyzed and researched extensively in the past 20 years as a pollutant that must be controlled. Among many other plastic products, the disposable drinking straw market projection is increasing; thus, it must remain a focus of environmental scientists. Due to their small size and lack of regulations, straws generally end up in landfills or oceans, where they degrade into micro- (MPs) and nanoplastics (NPs), which can cause serious health risks such as cancer and endocrine disruption. Polypropylene (PP) drinking straws annually contribute to about 109,500 tons of plastic waste in the US; if left untouched, this can generate, by a rough approximation, over 5.5 megatons of MPs over the next 50 years. Literature data were compiled for an MP bioaccumulation model to estimate human body exposure over intervals of one day, one year, and ten years for US straw consumers, comparing PP with polylactide (PLA), cellulose diacetate (CDA), and novel biopolymer-aragonite composite (BioCal™) straws. Replacing PP straws with these materials can lead to the elimination of up to 109,500 tons of plastic waste annually in the US, reducing both environmental plastic pollution and MP-related health impacts over the next 50 years, thereby eliminating up to about 5.5 megatons of MP and NP formation in the environment. Finally, the industrial biodegradation of the BioCal™ composite was evaluated.

1. Introduction

The United States utilizes approximately 390–500 million plastic straws every day [1,2] which is approximately 182.5 billion straws a year. Straws market report shows significant increase of straws production in North America which is expected to double by 2029 [3]. Thus, straw waste will demand twice as much attention from environmental scientists. Due to a lack of public awareness and environmental education, a significant percentage of these straws are disposed of improperly, ultimately ending up on streets or in the ocean. Consequently, it was found that nearly 7.5 million plastic straws litter America's shorelines [4]. According to a DataM Intelligence

market analysis, the majority of straws produced in the US in 2022 were made of plastic, among which polypropylene (PP) dominates [3]. Despite the fact that PP is a recyclable material, straw recycling presents significant challenges due to their small size and the difficulties associated with separating them from other municipal waste streams. Because PP is a non-compostable material, PP straws can persist in soil for hundreds of years. Furthermore, prolonged exposure to ultraviolet (UV) light and oxidation causes these straws to degrade into microplastics (MPs), which are recognized environmental pollutants. Numerous studies have demonstrated that MPs can induce carcinogenesis, neurological impairment, and reproductive toxicity. Consequently, sustainable alternatives to PP must be adopted for mass straw production to mitigate plastic and microplastic pollution.

Concurrently, sustainable and compostable alternatives—such as polylactic acid (PLA), cellulose diacetate (CDA), and polyhydroxyalkanoates (PHA)—are under active development and have entered commercial straw production in the United States. These compostable materials exhibit significantly lower or negligible MP emissions. However, each material presents specific limitations; for instance, PHA remains the most cost-prohibitive option. Meanwhile, PLA is inherently brittle, requiring plasticizers or blending with other biopolymers to enhance flexibility, ensure product quality, and prevent sharp edges during manufacturing. Because the cost of biopolymers remains two to three times higher than that of petroleum-based plastics, cost reduction is essential to facilitate adoption in high-volume, mass-market straw production.

Calcium carbonate (CaCO_3) composites have been utilized in the polymer industry since the late 20th century to reduce polymer consumption and lower production costs while simultaneously enhancing mechanical properties, such as impact resistance, durability, and tensile strength. One such commercially available composite is BioCal™, blend which contains aragonite (a form of CaCO_3). This renewable polymer filler was recently introduced to the market and is blended with other biopolymers to significantly reduce costs relative to neat polylactic acid (PLA) maintaining high mechanical properties required for high-volume straw production.

The objective of this study was to review major conventional plastic and bioplastic materials utilized in commercial straw production. Specifically, we evaluated individual PP straw plastic and microplastic (MP) emissions relative to polylactic acid (PLA), cellulose diacetate (CDA), PHA, and novel compostable BioCal™ composite straws. This was achieved by scaling up emission factors derived from recent literature to approximate total emissions for the entire disposable straws market in the United States. Furthermore, an attempt was made to predict consumer MP bioaccumulation resulting from long-term straw use and was projected over intervals of one day, one year, and ten years based on single-straw emission data for semi-quantitative scaling analysis data. Finally, using raw degradation, we modeled the long-term environmental accumulation of MPs (measured in metric tons) over 50- and 100-year horizons based on scenario semi quantitative scaling approximation to assess the pollution of PP, PLA, CDA and BioCal™ made straws.

2. Polypropylene Straws and its Environmental Impact

2.1 Straws Microplastics Emission

In 2015, 8.3 billion metric tons of virgin plastic were converted into finished products [5]. Only 9% was recycled [4] and 79% accumulated in landfills [5]. The majority of straws are made of plastic [3]. According to Potrykus et al. [6], PP can exhibit measurable structural changes and a degree of biodegradation after five years in a landfill; however, it largely remains undamaged. Even in Europe, where there is the highest concern about the environment and there are many facilities for composting, up to 25% of plastic waste is thrown away in landfills [6]. Potrykus et al. [6] collected PP waste samples directly from a landfill. By scanning electron microscopy (SEM), PP delamination was detected, which resulted in MP formation with particles smaller than $5\ \mu\text{m}$ [6]. These particles tended toward biodegradation and biofilm formation on their surfaces [6]. Similar results were found by Longo et al. [7] in recycled PP. In spite of biofilm formation, PP degradation is very slow, and the process strongly depends on the product's wall thickness, moisture, and soil microbiota. In drier conditions and the absence of relevant microbes that support enzymes, biodegradation will not take effect for decades. For example, Zhang et al. [8] examined recycled PP recovered after more than a decade of active burial, and the bulk physical integrity of the PP remained remarkably preserved. Only slow, local degradation was observed by the presence of carbonyl groups in the IR spectra. Experiments evaluating oxo-degradable and conventional PP films inside simulated landfill environments revealed that even PP modified with an oxo-degradable additive fails; though aimed at speeding up biodegradation, it showed a mechanical property loss of only 27% [9]. Interestingly, in both cases, the PP and the PP film with the oxo-additive were not found to be biodegraded, showing only a fragmentation of PP into small particles [9]. Utami et al. [10] studied PP straw MPs formation near Indonesia on Banten Bay. Such factors as photooxidation, photothermal oxidation due to heat, and mechanical abrasion are the major factors that cause PP to become brittle and break straws into smaller particles [10]. These MPs can easily be transferred by wind from the surface to water.

There are no long-term studies on PP degradation and biodegradation, but according to these data, it can be assumed that fragmentation will occur in PP straws over at least several decades, and the resulting MP degradation time will depend on environmental factors. Thus, PP straws can take up to 100 years to biodegrade if not recycled, which is a problem due to their small size, especially in arid deserts. During this period, PP can produce gas emissions contributing to the greenhouse effect. Over decades, PP straws will break down into smaller particles, ultimately becoming MPs and NPs (Fig. 1).

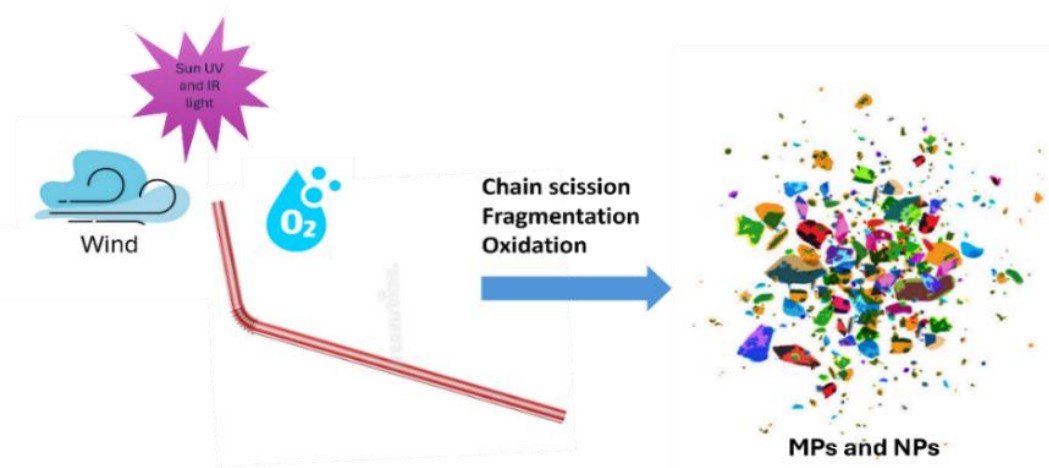


Fig. 1 Possible straw degradation environmental factors to microplastic formation

Microplastics (MPs) are plastic particles from 5 mm to 1 μm , is a widely accepted size nowadays for microplastics [5] and by some classifications 20 – 200 μm or up to 0.2 mm [11] whereas nanoplastics (NPs) are smaller particles size starting from 1 μm and lower and in some literature, they classified from 20 to 2 μm [12]. Thus, microplastic is a plastic which can be observed by eyes and smaller particles in a scientific optical microscope. Particles lower than the limit of optical microscopy can be observed only by more advanced equipment.

Micro- and nanoplastics have a severe impact on health. MPs are a major source of phthalate esters (PAEs) in aquatic environments, as PAEs are used as additives in plastics. Such PAEs have been detected in plastic drinking straws [13]. However, the concentration of PAEs in PP straws was lower than in polyvinyl chloride products in a laboratory simulation of PAEs release [14]. Over time, PAEs can accumulate in aquatic environments due to the persistence of PP straw pollution and subsequent MP generation. It was reported that the thermal stability of PP particles initially decreases and then increases as particle size further decreases to the nanoscale [15]. Thus, NPs represent a more persistent form of PP in the environment that can more easily penetrate the human body and cause health problems. Microplastics have been recorded in every coastal and marine habitat around the world. Long-term accumulation of MPs is associated with many health problems [16-21]. For example, numerous studies report that MPs are linked to different types of cancer [16-24] because they trigger uncontrolled cell proliferation [25,26]. Furthermore, MPs accumulate in the brain more than in other organs, especially NPs [17,20,21]. Notably, NPs can reach the brain quickly (within 2 hours) [16], and they may accelerate the progression of Parkinson's and Alzheimer's diseases [21,24]. Additionally, MPs can harm fertility and offspring development [30], while both NPs and MPs can induce inflammatory bowel disease [18-21]. Thus, MPs and NPs pose a global threat to the environment and food safety [19,29]. In response to MPs and NPs pollution, 150 local cities in California have implemented plastic bans [30].

As an alternative to petroleum-based PP, which generates persistent MP and NP waste, biobased and compostable materials have been applied to straw production.

2.2 Biopolymer Alternatives to PP Straws

2.2.1 Paper-Based Straws and Health Effects

There are several alternative materials existing on the market that aim to reduce the environmental impact of PP straws. One such widely used material is cellulose fiber in the form of paper, which serves as a compostable material. In Fig. 2, the North American straw market value is presented and compared to the overall material distribution. According to the global market report illustrated in Fig. 2, by 2025, paper straws were projected to lead the market segment with a share of 45% of the total market because of their affordability, availability, and adoption in the food service industry [31,32].

Paper straws have been produced for many years and their presence on the market became much greater after PP straws pollution confirmed. Paper straws have the advantage among other materials due to their easy customization e.g. the application of light reflecting foils, logo printing, different colored stripes attracting customer attention. Such straws degrade fast and do not remain plastic pollution, but at the same time it was found they have other effects described below. Despite their low cost and different customization options the downsides of using paper straws are the loss of structural integrity. This causes the straws to become soft or mushy.

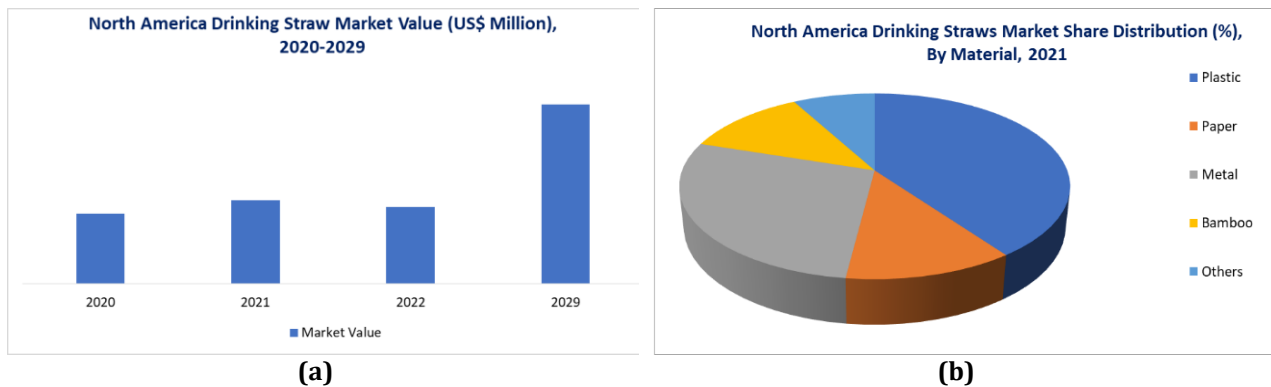


Fig. 2 North America straws market projection till 2029 (a); and market share straws distribution by materials they made of for 2022 (b) [3]

PLA and paper straws were compared for customer perception using a 19-question questionnaire format. Results published by Liang et al. [32] showed that the open structure of paper straws prompted water penetration and absorption, reaching a water absorption rate of 30% after 10 minutes, which can cause a noticeable difference in the taste of the drink. A biodegradable straw that can be easily inserted into a drink without fracturing may ultimately benefit merchant revenues [13]. Furthermore, some paper straws contain harmful additives, are challenging to recycle and degrade, and are ultimately not environmentally friendly [32].

It was documented in the Paper Straw Report from the USA White House that such straws have negative health effects because of the presence of toxic chemicals [33,34]. In 2025, President Donald Trump signed an executive order to switch from paper straws back to plastic straws, declaring paper straws “don’t work” [33,34]. Unfortunately, the decision was to move back to plastic straws which, as noted, are harmful to the body and environment. Researchers from the University of Antwerp, NL detected PFAS (polyfluoroalkyl substances) in paper and bamboo straws, which are also found in glass and plastic straws [35]. These substances are toxic and have a negative health effect, altering immune and thyroid function, causing liver disease, lipid and insulin dysregulation, and kidney disease, affecting the reproductive system, and causing cancer [36]. Paper straws can be coated by non-degradable polyethylene (PE) and polypropylene (PP) hydrophobic coatings, which can contain different toxic additives. While paper degrades fast, these coatings remain and degrade to micro- and nanoplastics, which pollutes the environment also causing health issues. There are several better options for plastic straws that meet health and environmental concerns and don’t have the big drawbacks that come with paper straws; Polylactic acid (PLA), cellulose diacetate (CDA), Polyalkenoate (PHA) to name a few.

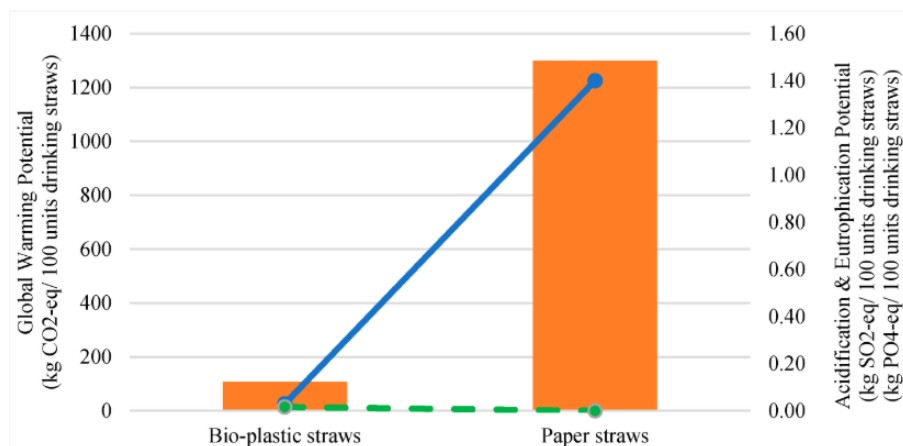


Fig. 3 Overall grand total of Global Warming Potential (GWP) for bio-plastic and paper straws [37]

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 [37]. As demonstrated by the comparative life cycle impacts in (Fig. 3), bio-plastic straws alternatives present a superior environmental impact to paper straws by exhibiting a substantially lower global warming potential (GWP).

2.2.2 PLA Straws

PLA is a well-studied compostable biopolymer produced from starch derived from high-amylose corn or sugarcane, and it is widely applied in sustainable packaging and automotive industries [38,39]. PLA has excellent transparency and good processing properties, which allow for its application in straw production via the extrusion process, but with some limitations. PLA by itself is a very brittle material, which creates difficulties during the straw cutting process. It easily fractures into sharp particles that can damage the mouth during drinking. Additionally, PLA is approximately twice as expensive as PP. Thus, different PLA composites and blends are a primary focus for manufacturers seeking to reduce the price through the addition of different fillers (e.g., starch, calcium carbonate, and talc) or blended bioplastics such as polybutylene adipate-co-terephthalate (PBAT). Regarding MP emissions, according to a recent report prepared by HYDRA Marine Sciences, PLA does not generate persistent MPs due to its propensity for hydrolysis. This makes it an excellent candidate for replacing PP, which forms persistent MPs. Lott et al. (2024) studied PLA microplastic formation using materials from several of the largest producers—including NatureWorks, Futerro, and Corbion—and found that PLA does not persist as MPs over time, ultimately degrading into biogases and water in the environment (Fig. 4) [40,41]. In the presence of water, the PLA polymer undergoes hydrolysis, breaking down into low-molecular-weight oligomers and the original lactic acid [42]. These more soluble products are subsequently metabolized by bacteria. Biodegradation and reduced microplastic persistence are strongly environment-dependent; incomplete degradation may occur outside optimal composting conditions.

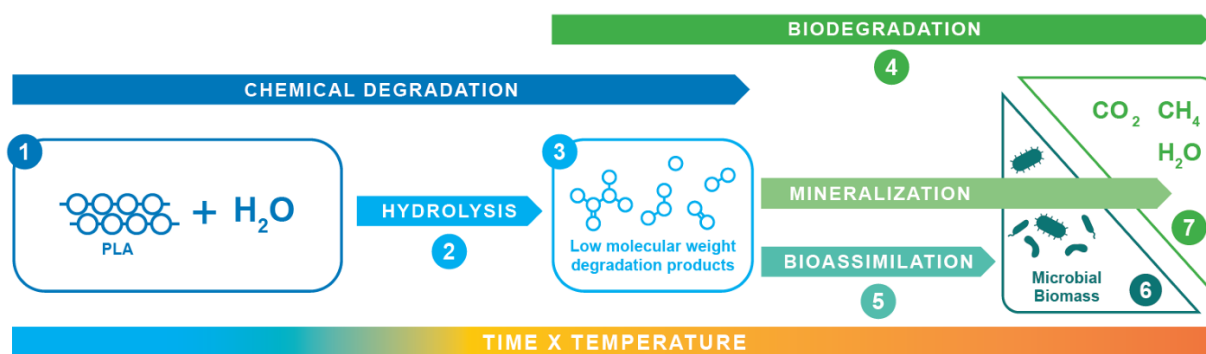


Fig. 4 Mechanisms for PLA Degradation [21]

2.2.3 PHA and CDA Straws

CDA- and PHA-based straws do not leave any microplastics, converting the entire bioresin volume into CO_2 , water, and biomass via naturally occurring microorganisms, according to a white paper by Eastman, one of the largest CDA producers [43]. PHA degrades through both intracellular and extracellular pathways, where microbes use the enzyme PHA depolymerase to break down the polymer [43]. This process completely turns the material into harmless final products, specifically CO_2 and water [44]. Straws utilizing cellulose diacetate do not leave any microbiobioresin traces after usage and biodegrade in under 12 months under home composting conditions according to TÜV certification [43,44]. The down-side is that home compostable materials are generally higher in cost than industrial materials, and in some cases, significantly higher than traditional plastics. The term “microbiobioresins” we introduced here is refers to microplastics produced by biopolymer resins as such PLA.

To address this issue, numerous blends based on different industrial- and home-compostable polymers with starch and polybutylene adipate terephthalate (PBAT) as a primary material or secondary additive, are commercially available. Each formula is designed to meet specific compostability criteria and can be validated through third-party testing and TÜV or BPI certification. Very rarely does a neat material go directly into production, because the polymer's properties must be adjusted to match processing equipment parameters and the requirements of the final product.

2.2.4 Bioresin Composite Based Straws

Many companies have spent a significant amount of investment to develop alternative materials for the plastic market. Combining different inorganic fillers—such as CaCO_3 , talc, and cellulose fiber—with organic fillers like starch has been widely used in the plastic industry for partial volume replacement to make materials more sustainable. One such material that was recently utilized as a filler is aragonite, a sustainable form of CaCO_3 produced by algae and bacteria during photosynthesis. This is a renewable, carbon-negative material because CO_2 is captured from the atmosphere during photosynthesis, rather than being emitted during the mining process of conventional CaCO_3 (limestone rock).

A few reports have documented aragonite application as a filler in polymer formulations [45-47]. Among laboratory-based research, it is necessary to highlight the mass-produced BioCal™ (NantBioRenewables LLC, AL, USA) composite containing aragonite, which is a patented blend [48]. It was proven that this filler is a carbon-negative sustainable mineral (carbon-negative certified by ISO 14067:2018 Carbon Footprint Analysis) [49] derived from Ocean Calcium Sand (OceanCal™), AL, USA [49,50] or oolitic aragonite, consisting of biogenic (Calcean, certified by ASTM D6866) CaCO_3 [49]. Aragonite is harvested from the bottom of the ocean. During aragonite formation, cyanobacteria capture CO_2 from the atmosphere for photosynthesis, instead of CO_2 gas being emitted as is the case in the mining process of land-based CaCO_3 .

Thus, BioCal™ composite comes with the added benefit of oolitic aragonite. When blended with other industrial compostable materials it provides an off ramp to one of the largest drawbacks to bioresin products, cost and sustainability. Industrial- and home-compostable materials are generally more costly than traditional plastic straws. Industrial compostable BioCal™ made straws are BPI certified according to ASTM D6400. Moreover, CaCO_3 in straws can speed up biodegradation [51,52] and can normalize soil pH after straw biodegradation due to a slight alkali reaction neutralizing acidity; it also works as a natural fertilizer for plants. The term “microbioresins” we introduced here is refers to microplastics produced by biopolymer resins as such PLA.

2.3 Straws Compostability Certifications

There are several common certifications used in industry for compostable straws. There are major Industrial Compostable certificates - BPI, CMA and Industrial Ok compost TUV and Home Ok Compostable (TUV) certificate. PLA based composites straws are subjected to BPI certification because industrial composting conditions are required for fast composting. Materials such as CDA, cellulose fiber and PHA are certified according to TUV Home OK compost. These materials do not require 3rd party composting and can degrade within 12 months in a normal landfill. This method is generally preferred as it eliminates the need to segregate products which is required when utilizing an industrial compostable material. PHA and CDA straws are subjected to TUV Home Compost certification as they don't require industrial composting conditions.

3. Literature Driven Straws Microplastics Emissions and Pollution Assessment During Timeline

Researchers from the Taiyuan University of Technology reported that straws emit microplastics during drinking [53], which are harmful to health. PP straws were compared with PLA-based straws for microplastic and microbioresin formation during a simulated drinking process using different beverage simulants (e.g., water, cola, and skim milk) [53]. For this experiment, Peng and Yu created a circulating system of interconnected PP or PLA straws connected to a pump on one side to mimic human drinking. The other end of the straw was placed inside a beaker containing 250 ml of simulant. After the simulation, the simulant liquid was filtered to collect emitted MPs or microbioresin particles, which were characterized by optical and SEM microscopy as well as FTIR/micro-FTIR spectroscopy [53]. It was revealed that PP straws emit more microplastic particles (26–28 particles per straw) than their compostable PLA counterparts (18–26 particles/straw) after five minutes of use [53]. To estimate approximate microplastic emissions from straws over time, the microplastic emissions of PP straws were compared to PLA and BioCal™-based straws based on SEM microscopy data for average MP diameter and size distribution of the released MPs in different beverages [53], combined with scaling-up factors (Supporting Information). The results are represented in Table 1.

The consumption of 1.414 mg of PP microplastics over one year is very low; however, over the course of 10 years, this amount increases to 14.14 mg. In addition to this value, we must also consider the bioaccumulation of MPs from daily life. For instance, we breathe air containing microplastic particles, and we consume MPs from morning coffee cups, food trays, and daily dietary sources such as fish and meat (which are already polluted by microplastics from the ocean). Thus, the final MP exposure level will be much higher. Humans constantly ingest tens of thousands to hundreds of thousands of microplastic particles annually. According to researchers' estimates, we ingest approximately 5 g of microplastics per week—the weight equivalent of a credit card [54]. The effect on overall health differs significantly between PP and PLA MPs due to the rapid degradation of PLA, whereas PP MPs accumulate over time. Thus, each straw adds a marginal burden of microplastics each year. Mostly large

microplastics are excreted, but smaller ones, especially nanoplastics, accumulate over time. In the case of PLA materials, the net plastic accumulation value can be considered zero due to PLA hydrolysis and its potential for full biodegradation within the body.

Table 1 *Straw's microplastic (MPs) emissions*

Material	MPs consumed by user per straw - 5 min usage, mg *	MPs consumed by user per year, if to drink one beverage per day, mg	MPs consumed by user if to drink one beverage a day for 10 years, mg	MPs consumed by all US citizens per day (500M straws)2, kg	MPs consumed by all US citizens during a year, kg	MPs consumed total by all US citizens over 10 years, kg and possible side effect
Polypropylene	0.0039	1.414	14.14	1.935	730	7,300 MPs non-degradable, persistent, accumulate in brains and other organs, can cause cancer.
PLA	0.0046	1.68	16.8, but can be equaled to 0 due to fully degradation	2.5	913, but can be equaled to 0 due to fully degradation	9,100, but can be equaled to 0 due to fully degradation
PLA based with Ocean Calcium Sand (BioCal™) **	0.0048	1.752	9.64, but can be equaled to 0 due to fully degradation MBR traces can degrade naturally in body due to PLA hydrolysis in acid of digestive system	2.4	482, but can be equaled to 0 due to fully degradation	4,800, but can be equaled to 0 due to fully degradation. MPs traces can degrade naturally in body due to PLA hydrolysis in acid of digestive system.

*Calculated for 27 microplastics per straw for PP and 22 microplastics for PLA based straws based on an average First major diameter observed in di-water according to statistical data, width of particles was taken as major diameter x 1/2 and particles height was measured from SEM images of corresponding microplastics [53], density for mass calculations was taken for amorphous PP and L-PLA. **BioCal straws MPs emissions are calculated based on PLA emissions [53] with adjustments (Supporting materials).

Limpiteeprakan et al. [55] compared biodegradation of PLA, PLA blends straws with PP straws. Straws made of PP didn't show apparent physical change or biodegradation observed on the surface and minimal weight change was observed when compared to compostable straws [55].

To estimate how much microplastics are generated by all straws in the US which can pollute air, soil, and oceans, the researchers took simple calculations represented in Table 2. One of the most regular straw weights is 0.6 g, thus it was multiplied to the yearly plastic consumption in the US by 500M straws [1,2] in order to calculate generated plastic waste.

PP straws create 109,500 tons of plastic waste each year only in the USA! Over 50 years, plastic waste will reach 5.5 megatons only from straws, which are hard to separate and recycle due to their small size. A large amount of this sum will go to oceans. Straws under UV radiation will slowly destroy, and if we assume that over a century, they will turn to microplastics, we will get a value of about 11 megatons of microplastics, which will fit

about 548,000 heavy-duty trucks to load if assume that each straw will turn to a 150-micron particle. Different degradation time of plastic materials is represented on Table 3.

Table 2 Possible straws' plastic and microplastics pollution (environmental-condition-dependent degradation)

Material	Single straw weight, g	Plastic waste generated during a year of 500M straws usage during a day, ton	Plastic waste generated during degradation of 500M straws usage a day over 50 years, ton	Microplastic waste generated during degradation of 500M straws usage a day over 100 years, ton
Polypropylene, non-compostable, non-biodegradable	0.6	109,500 Recycling is an issue ⁴	5,475,000	10,950,000
PLA, compostable, biodegradable	0.55	103,375	5,018,750, this value should be lowered to nearly zero because of degradation or 0 if industrially composted [40,56]	0, even if not industrially composted it will biodegrade and hydrolyze [40-42]
BioCal™ made	0.92	167,900	0, even if not industrially composted it will biodegrade and hydrolyze [40,55-57]	0, even if not industrially composted it will biodegrade and hydrolyze [40-42]
Wood based cellulose diacetate	0.7	127,750 or about 0 if home composted	0, if not composted, it will biodegrade in the environment during several years	0, it will biodegrade in the environment during several years

Table 3 Plastic states and approximate lifetimes in natural environments for three plastic films: PE, PLA and PHAs [58]

Transition state	Polyethylene (PE)	PLA	PHA
Macro and mesoplastic	Month to years	Months to years	Weeks to months
MPs and NPs	Hundreds of years	Years	Days to weeks
Soluble products	Weeks to months	Weeks to months	Hours

*Most persistent state.⁵⁸

If all citizens in the USA start using compostable straws, it will reduce microplastics generation only by straws up to 100%, and each year it will significantly decrease plastic waste up to 109,500 tons with good composting practice. This should result in microplastic body accumulation reduction and consequently a reducing of cancer cases, damaging to marine animals, including global plastic pollution reduction. Additional research is needed to estimate the health effect of bioplastics in human body. PLA straws can generate 103,375 tons of waste annually, but will degrade during years even if not industrially composted during approximately 6 months in moisture environment. The same with cellulose straws: CDA fully degrades in the environment if not home composted. For example, Aventa brand CDA made straws (Eastman) confirmed they don't remain microplastics in the environment (articles made from Aventa do not remain as microplastics in the environment) [43]. It is fully biodegradable under soil, fresh water, seawater, commercial and home composting according to ISO 14855, ISO 14851, ISO 17556 and ASTM D6691 Standard Test Method for Determining aerobic Biodegradation of Plastic Materials in the Marine Environment [43].

To determine the degree of physical disintegration of BioCal™ made straws when exposed to a simulated laboratory-scale composting conditions straws were tested according to ISO 20200. The experimental data is reported in Supporting materials.

NantBioRenewables confirmed that the biodegradation of BioCal™-based straws lasted 84 days and led to a 90% weight reduction, which was verified by an external straw study in a certified laboratory. For this according to ISO 20200 three batches of BioCal™ made black straws were placed inside a specially prepared compost and compared to degradation of a cellulose control. All samples were stored at $58 \pm 2.0^\circ \text{C}$. The bins containing the compost were weighed periodically throughout the 84 days. The composting material had a C:N ratio of 30:1 which was within the specifications for the test. The pH of the compost material at the start of testing was approximately 7.0, with a total dry solids percentage of 44.70% when dried at 105°C until a constant weight was reached. The volatile solids had a dry matter content of 94.90%. Mushroom compost had a C:N ratio of 13:1. After 84 days, a 90% weight reduction was observed in each bin where straws were placed for composting in triplicate. Thus, it was proven that BioCal™-based straws can degrade within about 3 months.

BioCal™ made straws are industrially compostable and presence of aragonite (CaCO_3) can speed up its degradation process because even at low concentrations it improves biodegradation by providing a pathway for microbial activity [57]. Notably, the BioCal™ composite offers the unique advantage due to its inclusion of ocean-sourced oolitic aragonite. By replacing PP straws with these sustainable alternatives, can effectively eliminate up to 109,500 tons of plastic waste annually in the U.S.

4. Socio-Environmental and Economic Impacts

Authors from the Woods Hole Oceanographic Institution estimated that 583 million straws leak into the environment in the U.S. annually, which leads to substantial environmental protection expenditures. Transitioning from plastic straws to compostable materials, according to their calculations, will save approximately \$150 million annually [58]. The 2025 BPI Summit in Atlanta highlighted a growing number of private composting facilities and networks across various states, alongside increased funding from agencies to open such facilities. These centers not only industrially compost PLA and other compostable products but also generate tax revenue for the government by providing composting services for local companies, including packaging and straw producers. Consequently, the production of biopolymer straws will have a profound socio-environmental and economic impact [55]. Over a projected span of 50 and 100 years, the production of compostable straws will reduce microplastic (MP) and nanoplastic (NP) accumulation by up to 5,475,000 and 10,950,000 tons, respectively, thereby lowering healthcare expenditures and cancer cases among the US population. Additionally, the government should promote the production and widespread use of these bioplastic straws to replace PP plastic and PFAS-containing paper variants.

5. Conclusion

This work provides a semi-quantitative, literature-driven assessment of microplastic emissions associated with disposable straws by integrating per-item emission data with national consumption. Literature data suggest PP is a persistent long-term source of MPs, while compostable alternatives may reduce persistence under suitable conditions; however, outcomes depend on waste management and environment. Plastic PP straw pollution is remarkably high and is projected to increase over the coming years, leaving behind an enormously high volume of microplastics over the next several decades. This study estimated the potential plastic and microplastic pollution, including the long-term microplastic intake derived specifically from straws. Collectively, all US citizens could ingest up to 730 kg of PP microplastics annually from straws alone at environmental-condition-dependent degradation. With an annual contribution of about 109,500 tons of plastic waste in the U.S. alone, polypropylene (PP) straws represent a significant environmental threat; over a century, PP straws can generate approximately 548,000 heavy-duty truckloads of MPs (11 megatons). This will drastically pollute the environment and consequently can increase MP intake through air, water, and food. MPs and NPs pose serious risks to both marine ecosystems and human health, including carcinogenic potential. These findings represent scenario-based projections highlighting relative trends rather than precise predictions. Furthermore, transitioning to paper straws does not yield a positive effect on human health because of the presence of PFAS. Moreover, paper straws have significantly higher Global Warming Potential compared to bioresins. All of these issues require immediate and innovative solutions in the form of compostable materials. Further experimental validation and lifecycle studies are required and more research is needed to study the biodegradation timeline of biomicroresins within the human body.

Supporting Information

Supporting materials are available upon request.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of this paper. The authors declare no competing financial interest.

Author Contribution

Andrey Tyuftin: **Methodology, Resources, Data Curation, Writing - Original Draft, Visualization, Project administration.** Kenn Budlong: **Conceptualization, Data Curation, Writing - Review & Editing, Supervision, Project administration.**

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