Evaluation and future development direction of paper straw and plastic straw

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Abstract—In recent years, plastic pollution has become one of the environmental issues of concern. This article explores the hazards of plastic straws and analyzes whether the decision to replace plastic straws with paper straws in the context of plastic restriction is entirely environmentally friendly. The results show that plastic films used in agricultural production remain in the soil after weathering and degradation, affecting soil structure, water and nutrient transfer processes, secondary salinization, and hindering plant growth. Microplastics in terrestrial and marine ecosystems are taken up by and accumulate in organisms and enter the human food web, affecting the human central nervous system and reproductive system. This article concludes that paper straws contain harmful additives, are challenging to recycle and degrade, are costly to build, are not environmentally friendly, and have a low promotional rate by studying their life cycle, content, recycling rate, degradation rate, usage problems, and applying. The paper also introduces the advantages of some new green straws, such as bamboo straws, wheat straws, PLA straws, and stainless-steel straws, which are environmentally friendly, durable, biodegradable, recyclable, and reusable. This essay aims to find better alternatives to address the potential environmental problems associated with plastic straws and mitigate the environmental hazards associated with the use of plastic products.

1. Introduction
Plastic products are light, cheap, durable, corrosion-resistant, and have good thermal and electrical insulation properties. We take advantage of these characteristics to manufacture a large number of products that cover almost all aspects of daily life and bring social benefits such as health, safety, material protection, energy-saving, and medical progress [1]. However, more than 50% of artificial plastics are disposed of after single use, resulting in 150 million tons of plastic waste every year in the world. Plastic straws and stirrers account for 7% of the total plastic waste [2, 3]. In the absence of waste management facilities, these plastics will be leaked into aquatic or non-aquatic ecosystems and then degraded slowly, affecting ecosystems and human health [4]. In order to manage litter and reduce non-
recyclable materials, more and more local municipalities enact plastic ban as a management means, including but not limited to straws [5]. For example, 150 local cities in California have implemented plastic ban and EU issued a legislation to curb single-use plastics in 2019 [5, 6]. Similarly, Canada plans to ban harmful single-use plastics as early as 2021 [7]. However, some argue that these plastic bans ignore the needs of patients and persons with disabilities [8]. So, it is urgent to find alternatives to single-use plastic straws in order to meet the requirements.

Many people propose to replace plastic straws with paper straws, and they believe paper straws were found to perform better or on the same level with polypropylene (PP) straws in terms of environmental impacts [9]. However, the stability may hinder the popularity of paper straws as they get soggy quickly [10]. In the process of popularizing the use of paper straw, other problems gradually emerged. Bin Jia designed a paper straw composed of 60g outer kraft paper and 120g inner kraft paper, and the outer kraft paper was printed with colorful or complicated patterns [11]. He believed that this new paper straw has the advantages of being recyclable and reducing plastic pollution [11]. However, the issues considered in this design are not comprehensive enough. For example, whether the material of the paper straw and the chemical substances in the printed pattern will dissolve into the drink, whether it can be recycled entirely and biodegraded, and whether it can be promoted in society.

The primary purpose of this article is to analyze whether the decision to replace plastic straws with paper straws in the context of plastic restriction is completely eco-friendly or whether paper straws are an environmental hazard. To begin with, we briefly introduced the environmental and health hazards of plastic straws and the advantages of paper straws as an alternative to plastic straws. Then we expanded on the disadvantages of paper straws in various aspects (toxic substances, recycling rate, degradation difficulties, and diffusion). In the end, based on the disadvantages of replacing plastic straws with paper straws, we give examples and prospects of other alternative eco-friendly straws (bamboo, wheat, PLA, stainless steel, etc.).

2. Impact of plastic straws

2.1 Impact on the environment

At present, many studies have determined the impact of plastic waste on the marine ecosystem [4]. The life and stability of plastics will make them exist in the ocean for a long time, and its consequences include entanglement with aquatic organisms (such as seabirds, returnees, mammals, fish, invertebrates, etc.), destruction of habitat, species transportation, and intake [12]. Plastic straws cannot be completely biodegradable. Instead, they will be degraded into plastic fragments, i.e., microplastics. Microplastics have been recorded in every coastal and marine habitat around the world. They can be ingested or inhaled by seabirds and pelagic fish feeding on the water surface. The adverse effects of this process may include intestinal blockage, weakened feeding stimulation, reduced steroid hormone levels, delayed ovulation, and reproductive disorders [12-14]. In addition, harmful substances released from plastic products, such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, petroleum hydrocarbons, and other organic pollutants, will adversely affect aquatic organisms. If aquatic organisms ingest plastic fragments, toxic substances may be transferred to the food chain [12, 15].

Plastic pollution endangers not only freshwater and marine ecosystems, but also affects agricultural ecosystems. For example, plastic film is widely used in agricultural production. After weathering and degradation, many plastic film fragments remain in agricultural soil, affecting soil structure, water, nutrient transmission, and secondary salinization and hindering plant growth [14, 16]. Plastic film fragments retained in the soil may also flow into the ocean through runoff [14].

2.2 Impact on human

In the industrial production of plastics, the primary polymer resin is usually mixed with various additives to improve product performance, such as heat stabilizer, colorant, ultraviolet stabilizer, plasticizer, etc. [17]. These additives have potential toxicity, such as dibutyl terephthalate [15]. However, the impact of plastic additives on the human body is controversial because the impact is related to the type, dose and
biological absorption, and accumulation of additives. For example, the additives of phthalates, bisphenol A, BPA, and other plastic products may have adverse effects on human endocrine function and reproductive development [1, 15]. At present, the research on the impact of plastic additives on the human body faces great difficulties, such as the change of plastic and additive production mode, low-dose chronic exposure of plastic additives, the confidentiality of industrial production, etc. Therefore, we also need to study the relationship between the leakage amount of toxic substances from plastics and time, the mixing effect of different chemicals rather than similar chemicals [15].

In addition, plastic straws are degraded into microplastics in terrestrial and marine ecosystems. They will be ingested by organisms, accumulate in the liver, brain, and other tissue, and enter the human food web. Theoretical studies have shown that plastics may affect the central nervous and reproductive systems when the exposure level is exceptionally high [18].

3. Paper Straws

3.1 Advantages of paper straws

Compared to plastic straws, Paper straws can be produced in different diameters and sizes and customized with colors and branding. Second, the paper has the advantage of being naturally degradable and reusable, such as re-pulping into newspaper or booklet paper. For instance, the shelf life of paper straws is longer, and the price is low; PLA straws can be stored for about one year, whereas paper straws can be stored for two to three years; the cost of producing a PLA straw is 0.05 yuan, and the cost of producing a paper straw is 0.03 yuan (CCTV News). Therefore, paper straws are currently the most cost-effective alternative to plastic straws [19].

3.1.1 Life cycle assessment of plastic straws

Life cycle assessment (LCA) is a method used to evaluate the environmental impact of products in the whole life cycle. The life cycles of paper straws and plastic straws products are paper starts from logging, plastic starts from oil exploitation, products are manufactured and used by the public in life, and some valuable parts are recycled until final combustion [20]. Roy et al. summarized the LCA research results of different types of straws by different researchers [4]. The results showed that the greenhouse gas produced by paper straws in the life cycle was much less than that of plastic straws (Table 1).

3.1.2 Life cycle cost of plastic straws

The life cycle cost (LCC) of straws depends on the costs associated with materials, manufacturing processes, transportation, and disposal. Roy et al. synthesized the research results of LCC of various types of straws [4]. The results showed that the cost of paper straws was four times that of plastic straws (Table 1). Urquhart found that the cost of paper straw is currently ten times that of plastic straw [21].

| Material | Dimension, mm | System boundary | GWP, g CO₂ eq | Cost, $ | Source |
|----------|---------------|-----------------|--------------|--------|--------|
| PP       | –             | Cradle-to-grave, landfill | 5.82        | 0.01   | [22]   |
| PP1      | L: 225; D: 6  | Cradle-to-grave, incineration | 2.92        | –      | [23]   |
| PP2      | L: 225; D: 6  | Cradle-to-grave, landfill | 2.44        | –      | [23]   |
| PP       | L: 140; D: 4.3| Cradle-to-grave, landfill | 1.46        | 0.003  | [24]   |
| Paper    | L: 190; D: 6.4| Cradle-to-grave, landfill | 1.38        | 0.04   | [24]   |

PP: polypropylene; GWP: global warming potential; L: length, D: diameter.
3.2 Disadvantages of paper straws

3.2.1 Poisons in Paper Straw

The main safety risks of paper straws are the migration of harmful substances that may exist in the process of use into the food, such as heavy metals in the ink, fluorescent substance, formaldehyde, etc. that are introduced or unintentionally added during the production process; There may be microbial contamination in the process of circulation [25]. There is a unique food safety control standard for paper and paperboard in China, namely GB4806.8-2016 "National Food Safety Standard for Food Contact Paper and Paperboard". This standard covers heavy metal, physicochemical standards, microbial limits, sensory requirements, etc., regarding the safety of food contact paper and cardboard as shown in Tables 2, 3, and 4. In addition, if adhesives and inks are used in the products, they must also comply with the corresponding national food safety standards. Ensure that when the product is in contact with food under regular use, the substances that migrate into the food do not harm human health and do not cause changes in food composition, structure, color, flavor, and other properties [25].

| Table 2. Sensory Requirements [25] |
|-----------------------------------|
| **Items** | **Requirements** |
| Sensory | Normal color; no peculiar smell, mildew or other dirt |
| Soak Solutions | The soaking solution obtained from the migration test should not have coloration, odor and other sensory deterioration |

| Table 3. Physicochemical Standards [25] |
|---------------------------------------|
| **Items** | **Requirements** |
| Lead(Pb)/(mg/kg) | ≤ 3.0 |
| Arsenic(As)/(mg/kg) | ≤ 1.0 |
| Formaldehyde/(mg/dm³) | ≤ 1.0 |
| Fluorescent Substance | Negative |
| Wavelength 254nm and 365nm | |
| Total Transfer Volume | ≤ 10 |
| KMnO₄ Consumption | ≤ 40 |
| Heavy metal/(mg/kg) | ≤ 1 |
| 4% acetic acid(volume fraction) (60°C, 2h) | |

| Table 4. Microbial Limits [25] |
|-------------------------------|
| **Items** | **Limitation** |
| Coliform/(50cm²) | Must not be found |
| Salmonella/(50cm²) | Must not be found |
| Mould/(CFU/g) | ≤ 50 |
3.2.2 Recovery rate of paper straws
Food contamination and non-biodegradable material laminates reduce the recycling rate of paper straws. Most recycling facilities cannot accept paper products that have been contaminated with food, such as liquid-soaked paper or grease-stained pizza boxes. The special features of paper straws and the hydrophilic nature of their materials make them more susceptible to food contamination. As a result, liquid-soaked paper straws cannot be recycled or reused but rather are treated as other waste. To strengthen the stability of paper straws in the market, manufacturers apply a coating on the interior of paper straws to protect them from water and oil, which is usually made of polyethylene (PE) or polypropylene (PP) [26]; these coatings, however, are non-biodegradable, non-repulpable, environmentally harmful, and difficult to separate from paper for recycling. Ultimately, these non-recyclable paper straws are disposed of in suburban incineration plants or landfills, and the long transport distances make the disposal of paper straws more expensive and complex [27].

3.2.3 Degradation Problems
Per- and polyfluoroalkyl substances (PFAS) were detected in many commercially-available plant-based drinking straws. Leach tests were performed with brands with the highest average total concentration of PFAS to assess the ability of different compounds to migrate to water at three different initial temperatures (Fig. 1). At the three temperatures (4℃, 20℃, and 90℃) about two-thirds of the extractable PFAS dissolved in water, without statistically significant difference between them [28]. These substances give the paper straws water-resistant properties, and although they have hazardous and bioaccumulative nature and are being phased out voluntarily in the United States, they are still continuously detected [28]. Paper straws will biodegrade within a few weeks in nature if the straws are made out of pure paper with no traces of any toxic chemicals or plastic lining. Unfortunately, many products advertised as biodegradable, especially paper products, have been confirmed to contain PFAS [28]. Whether it is sent to a landfill or a commercial composting facility, the PFAS in these products is difficult to separate. As a result, the entire straw itself may not be completely degraded for hundreds of years, and PFAS eventually migrates into the environment through the landfill’s leachate [28].

![Fig. 1 Total PFAS concentrations in the water leaching experiment](image_url)

3.2.4 Usage Problems
In 2021, Zhejiang Province Consumer Insurance sampled paper straws from 10 catering stores in Hangzhou city. The tests found that the potassium permanganate consumption of two batches of samples didn’t meet the national standards (the test result is 52mg/kg and 64mg/kg). Besides, one batch of
samples showed degumming and delamination under the test conditions of "water temperature of 60 degrees Celsius and water capacity of 0.5 liters", and this result indicated that the temperature resistance performance did not meet the requirements.

The paper straw consists primarily of hardwood fibers and is hard sizing with a hydrophobic sizing agent to achieve water contact angles of 102° to 125° [29]. All assessed straws lost 70 to 90 percent of their compressive strength after less than 30 minutes in contact with the liquid, and the paper straws absorbed about 30% to 50% of the weight after 30 minutes of liquid exposure [29]. In addition, The high-temperature liquid leads to the decrease of the compressive strength and the increase of liquid absorption [29]. That is why many people complain that the straw is easily broken when drinking.

In 2018, in order to evade the condemnation of European environmental agencies, McDonald's began to use paper straws in the United Kingdom and Ireland restaurants. However, consumers criticized the paper alternatives that environmental protection and taste are sometimes incompatible — paper straw was easily broken within minutes of use [30]. After complaints from consumers, the company thickened the version of the straws. However, the versions were too thick to be recycled by garbage disposal companies. So, the effect of replacing the paper straw on eco-friendly may not be as great as imagined.

3.2.5 Promotion of paper straws

High costs and poor user experience have hampered and spread of paper straws. Although the price of paper straws has a significant advantage over other new eco-friendly straws, the cost of paper straws is still ten times higher than that of traditional plastic straws. On Amazon.com, $16.99 buys only 300 10.25-inch paper straws, while $6.99 buys 300 10.3-inch plastic straws.

Since September 1, 2020, when China began to implement the People's Republic of China Law on the Prevention and Control of Solid Waste Pollution, industries have been restricted or banned from using plastic products, and paper-based environmentally friendly products have begun to gain popularity. The massive demand has led to rising raw materials for pulp, increased transportation costs, and increased tariffs [27]. The increase in raw material costs has made manufacturers who use paper straws instead of plastic straws face high production costs and conflict with the traditional sales strategy of manufacturing plastic straws at thin margins, so most straw manufacturers are faced with the state of high-cost production difficulties.

For merchandisers, straws are a gift that must be provided by the seller when a customer purchases a product. When a merchant replaces a plastic straw with a more expensive paper straw, it leads to a decrease in expected revenue, so the merchant has to increase the unit price of the product to balance the financial loss of using a paper straw, and finally, the individual consumer needs to buy the product at a higher price.

The experience of using paper straws is not good and the biggest problem is the weak stability of paper material which is readily decomposed by water [31]. Since the first implementation of paper straws in McDonald's in the UK in 2018, there have been a lot of complaints (BBC News), such as paper straws have a "pulpy taste" that affects the taste of drinks, tend to soften, and bend in hot drinks and are not easy to suck. In order to boycott paper straws, some people even launched a joint protest asking McDonald's to bring back plastic straws.

4. New Alternatives

Straw is part of a global public outcry, with many consumer-led campaigns calling for replacement or an outright ban on plastic straws, and some alternatives can replace plastic straws and paper straws [32]. Straw life cycle stages are shown in Fig.1. Theoretically, bamboo straws are the most environmentally friendly choice. Bamboo proliferates and can release oxygen before they grow into mature bamboo suitable for making straws. Wheat straws are 100% biodegradable, and although it is relatively thin, it will not become soft due to soaking. For high-traffic bars, wheat straws provide the convenience of disposable straws, but the environmental impact caused by them is very low.

In a strategic sense, biopolymers synthesized from natural sources are considered attractive and alternative alternatives to synthetic polymers in various aspects, as shown in their life cycle assessment
(LCA) [33]. Some biopolymers, such as polylactic acid (PLA), were found to be naturally biodegradable. PLA straw is a starch-based polymer made from corn. It can be recycled or composted. Compared with traditional plastics, fewer fossil fuels are consumed in the production process. Take South Africa as an example. Reusable glass straws are made of imported silicate glass tubes [32]. Based on their reusing purpose, the straws are designed to be handwashed and often sold with brushes, and subsequently air-dried [32]. Stainless steels are solid and durable, so it rarely needs constant updates. Similar to glass, stainless steel are hand-washable and air-dried between uses [32]. Furthermore, steels are highly recyclable; thus, it is assumed that steel straw will also be recycled to a certain extent.

| Polypropylene | Paper | Polylactide | Glass | Stainless Steel |
|---------------|-------|------------|-------|----------------|
| Polypropylene production | Kraft paper production | PLA pellet Production | Glass tube production | Steel tube production |
| Straw manufacture | Straw manufacture | Straw manufacture | Straw manufacture | Straw manufacture |
| Distribution | Distribution | Distribution | Distribution | Distribution |
| Retail | Retail | Retail | Retail | Retail |
| User | User | User | User | User |
| Marine Environment | Open Burning | Dumps | Landfill | Recycling |

Fig.2 Straw life cycle stages [32]

5. Conclusion
In these years, the massive use of plastic straws exacerbates environmental problems, such as causing soil degradation, damaging marine ecology, and polluting the food chain. In order to reduce the state of plastic pollution, most countries have explicitly banned or restricted the use of plastic products, including the use of plastic straws. Plastic has always been a popular packaging material in the food industry, but it has become a source of environmental pollution because of its harmful effects on humans and the environment. Paper straws have become the number one alternative to plastic straws because of their price advantage, ease of customization, and longer shelf life. In order to explore whether paper straws meet environmental standards, this paper analyzes five aspects of paper straws, including their contents, recycling, degradation, use issues, and promotion. The results show that paper straws contain harmful additives, are challenging to recycle and degrade, have high costs and low promotion rate, and
pose a specific burden and potential threat to the environment and human body. In order to find a better alternative to plastic straws, this paper analyzes the advantages of several new environmentally-friendly straws. Such as bamboo straws, wheat straws, PLA straws, and stainless-steel straws these straws have the advantages of being environmentally friendly, durable, biodegradable, recyclable, and reusable respectively. Finally, it is hoped that more environmentally friendly, sturdy, economical and publicly acceptable straws will emerge to solve the problem of straw use in the restaurant industry and alleviate the environmental problems caused by urgent plastic pollution.

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