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An Innovative Alternative to Plastic Straws with Bacterial Cellulose

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ABSTRACT

This study aims to introduce the usage of biodegradable bacterial cellulose as an alternative material to straw production. Cellulose is a crystalline linear chain polysaccharide found in various organisms with cell walls. Known for its strength and durability, cellulose is also biodegradable due to its organic nature. Through a series of different experiments that include the production of cellulose from SCOBY (symbiotic culture of bacteria and yeast) and the subsequent creation of straws from the cellulose and food-safe glue, this study proposes a more environmentally friendly alternative to plastic straws. Further experiments were done to compare the functionality of the cellulose straw to that of plastic straws and other alternatives currently in the market, including paper and metal straws. This was done using a strength test to see how much weight the straws could hold before breaking, a test to see how long the straws could maintain their integrity with water running through them, and an experiment where different drinking liquids were used. It was found that the cellulose straws displayed no loss in functionality when compared to the other straws and displayed similar levels of durability as the plastic straws.

Introduction

The usage of plastics has become increasingly prominent around the globe as growth in emerging markets has increased the consumption of cheap yet versatile material. Production of plastics has quadrupled in the last 30 years - nearing 460 million tons of plastic in 2019 - while waste generation reached 353 million tons in that same year. Furthermore, only 9% of disposed plastics are recycled, while the remaining amount is in landfills or burned, causing them to leach into the local ecosystem and nearby aquatic environments. As of 2019, it is estimated that 30 Mt of plastic waste has accumulated in seas and oceans, and a further 109 Mt of plastic waste ended up in rivers (*Plastic pollution is rowing relentlessly as waste management and recycling fall short, says OECD*, (OECD), n.d.).

The increase of plastic waste in natural environments can be explained by the increased production and ineffective disposal and the molecular structure of plastics that prevents effective biodegradation. The second most common plastic, polypropylene polymer, is found in objects such as straws. Formed by thousands of organic subunits originating from petroleum-based substrates and linked together by covalent bonds, polypropylene is characterized by its structural stability and resistance to stress cracking. These features have made it a popular choice in manufacturing, but its stability works against microorganisms and environmental factors that work to degrade plastic (Jeon et al., 2021b). It is estimated that polypropylene degrades at a rate of 10μm a year, suggesting that complete degradation could take centuries, if not longer (Chamas et al., 2020b). A recent estimate suggests that the U.S. uses 500 million straws daily (*The Be Straw Free Campaign (U.S. National Park Service)*, n.d.). The single-use nature of straws, in combination with such extensive decomposition times, causes them to accumulate quickly in landfills.

With respect to improperly disposed plastics that end up in natural habitats, the larger plastics become physical hazards through entanglement, ingestion, and smothering of wildlife (Rochman, 2013). As the larger plastics continue to degrade, they form small-chain polymers, oligomers, and monomers which are known as microplastics. As these microplastics continue to accumulate in local ecosystems, they are ingested by organisms and passed down the food chain. Many of these microplastics shed carcinogenic and estrogenic substances, environmental contaminants, toxic compounds, and heavy metals. As they pass from organism to organism, they accumulate in the cells of both vertebrates and invertebrates and exert a toxic effect (Rochman, 2013), (Wu et al., 2021). Additionally, if microplastics are ingested, they can cause blockages of the gut tract that result in pseudo-satiety sensation and physiological stress, alteration of the feeding and retard of the growth, reduction in fertility, fecundity, and survival rate of progeny as nearly all organisms lack specific enzymatic pathways to break down microplastics (Killham & Prosser, 2015).

In order to combat the increased usage and disposal of plastics, alternative material is needed for manufacturing needs. SCOBY, Symbiotic Colony of Bacteria and Yeast, is a symbiotic fermentation culture that is commonly used during kombucha tea fermentation. In this fermentation process, the predominant organisms used in North America are the yeast genus *Brettanomyces* and the bacterial genus *Komagataeibacter* (Harrison & Curtin, 2021). These organisms produce microbial cellulose by oxidation of glucose to gluconic acid and the synthesis of uridine diphosphate-glucose that creates microbial cellulose that remains on the liquid surface. Cellulose consists of long chains of glucose connected by beta-1,4-glycosidic linkages that hydrogen bond together to create microfibrils. The organization of these microfibrils confers strength, durability, and flexibility, which are characteristic of cellulose, making it a potential alternative to a more popular material such as plastic (*The Be Straw Free Campaign (U.S. National Park Service)*, n.d.). Additionally, as cellulose is pervasive in plant structures and is important for ecosystem productivity, various soil bacteria and fungi have the necessary enzymatic pathways to break down and recycle cellulose (Lustri et al., 2015). Due to its inherent structural strengths, simple manufacturing process, and biodegradable nature, cellulose is a potential substitute for plastic in producing products such as plastic straws.

Materials

Fermentation Process

- 290 grams of brown sugar
- Three wooden spoons
- 4 different glass containers (26 cm by 37 cm by 6 cm)
- Balance scale
- 8 black tea bags
- A total of 28 cups of boiled water to be distributed according to the size of the container
- 4 different SCOBY bacterial cultures
- Kombucha starter tea (100 mL for each container)
- Beaker (250 mL)
- Thermometer
- 4 thin cloths

Drying Process

- 10 Plastic Straws
- 10 Paper Straws
- 10 Metal Straws
- Food-safe glue
- Humidifier
- Transparent container
- Lamp
- Freezer
- Linseed oil
- Tung oil

Testing Process

- String
- Weigh boat
- 500 g of sugar
- Two wooden blocks
- Protractor
- Funnel
- Timer (phone)
- 100 mL Graduated Cylinder
- Hose
- Tape
- Can
- Paper Twist
- Rod

Methods

Synthesis of Cellulose

To synthesize cellulose, we initiated the process of kombucha fermentation. We poured 8 cups of boiling water into a glass container. We then placed two black tea bags into the boiling water and stirred for 15 minutes to ensure that the black tea had dispersed through the water. After stirring for 15 minutes, we measured 80 grams of brown on a balance scale and poured it into the solution. The stirring continued for another 15 minutes (Johnsen, 2014).

Black tea and brown sugar are essential nutrients that aid the proper development of the SCOBY bacteria. Black tea consists of high concentrations of purines that are essential in aiding microorganisms in specific metabolisms, such as bacteria, to thrive in kombucha fermentation (Llc, 2019). The brown sugar consists of sucrose, an important disaccharide for yeast in the SCOBY to feed on (*Does Sugar-Free Kombucha Exist*, n.d.)

Figure 1. Initial process of kombucha fermentation with SCOBY and sugar-black tea mix solution to feed the bacterial culture

Figure 2. Cellulose signs from SCOBY in kombucha fermentation

Figure 3. The final stage of kombucha fermentation is where cellulose is developed from the SCOBY

We used a thermometer to measure the temperature of the solution to ensure that it had cooled down to room temperature, making it safe to insert the SCOBY into the solution. Once room temperature was reached, we inserted the SCOBY and 100 mL of kombucha starter tea. The kombucha starter tea is necessary to introduce the bacteria, yeast, and SCOBY to the solution to initiate the fermentation process. We waited 1-2 weeks before signs of cellulose started to develop (Johnsen, 2014).

Figure 4. Bacterial cellulose extracted from the solution successfully

Drying of Cellulose around Straws

Since the cellulose directly came out of the kombucha tea under the cellulose, the cellulose was still wet. We quickly extracted the cellulose from the container. We placed the thin layer of cloth onto the container again to ensure that no contaminants from the air would contaminate our solution. To properly mold cellulose into a straw-like shape, we cut thin slices from the cellulose and wrapped them around the different types of straws. Before wrapping the cellulose around the straw, we want to ensure that the cellulose doesn't stick to the straw, which would make cellulose more difficult to remove.

Figure 5. Bacterial cellulose being molded on different types of straws: paper, plastic, and metal

To not have cellulose stuck onto the straws, we applied a neutral oil (specifically vegetable oil) onto each straw. We used vegetable oil because it's a lubricant, meaning that vegetable oil would provide low viscosity that would reduce the friction of the cellulose and the straw the cellulose would hold onto. We wrapped the cellulose around the straws with the applied vegetable oil and secured the structure by applying food-safe glue to the ends of the cellulose. We determined our locations of drying of the cellulose straws according to different temperature conditions: in a freezer, under a lamp, and at room temperature.

Figure 6. Bacterial-cellulose straw molded from a plastic straw structure (final drying process)

To enhance flexibility, strength, and water resistance, we applied tung oil and linseed oil to the surface of the bacterial cellulose. These oils are hydrophobic, meaning that they tend to repel water. According to Eva Durance's experiment of creating a wallet out of bacterial cellulose, the applications of tung oil enhanced the flexibility and strength of the cellulose. In contrast, the linseed oil improved the water resistance of bacterial cellulose (*Scoby Textiles Part 2*, 2019). After the bacterial cellulose dried, we carefully removed them from the straws.

Figure 7. Bacterial cellulose straws applied with different oils: linseed and tung oil

Testing Characteristics

Flexibility

The first property we wanted to test was the flexibility to see if our cellulose straw's structure could bend without breaking. People tend to bend straws to have the appropriate angle that suits them comfortably while they're drinking out of their preferred drinks. We started our cellulose straw at a 180-degree angle, which is the initial angle of the straw. At one end of the straw, we slowly bent the straw from the center. We measured the angle of the protractor when the cellulose straw broke. We repeated the process with different types of straws to compare the angle of when the straws broke.

Durability of Usage

An important characteristic of straws and their alternatives is that they maintain their integrity as they continue to be used. This leads to the second property tested, the durability of the straw as it is used. In order to test this in a standardized manner, water was poured into the straws through a funnel at a constant rate. Duration until observable structural differences formed was used to compare the performances of the different straws. In preparation for testing the durability, we used a paper twist to tie the ends of the straws against a rod to keep it firmly vertical. We then placed a funnel on top of the straws and a hose connected to a water source into the funnel. We let the water run into the funnel at a constant rate and placed a graduated cylinder under the straw to measure the rate at which water flowed through. We adjusted the flow so that water would pass through the straw at a rate of 500 ml every minute. When we started our trials, we would start a timer and observe the straws until we observed any qualitative changes in the structure. We then would let water flow through until the straw broke. If no structural differences were observed, we would let the experiment run for one hour to standardize the process.

Tensile Strength

Tensile strength is the amount of resistance a material can maintain while being stretched under tension. Tensile strength is another physical property that is necessary for straws to test if they can still maintain their structure even under a lot of tension and stress. We wanted to see how long it took for our cellulose straw to break by consistently adding more weight to it, ultimately testing the tensile strength of our straw. To initiate this process, we placed the ends of our straw on two wooden blocks and taped the ends of the straw. We then tied a string around a weighing boat. The weighing boat will be used to consistently add weight to the straw. At the center of the straw, we then tied the string to the center of the straw to connect it with the weighing boat. We gradually added grams of sugar to the weighing boat after every time the straw was in a stable structure. Once the straw broke, we recorded the mass at which the straw broke and recorded the force.

Vertical and Horizontal Compression

Straws typically have a rigid structure that is mostly stable and can withstand high pressure. We wanted to test how sturdy the structure of our straw is, both vertically and horizontally. These two procedures are mostly the same, except for the position of the straw. We first placed the straws in a vertical or horizontal position. To secure the straw to prevent movement, we placed the straw vertically, similarly to the durability test, and taped the straw's ends onto the table for the horizontal test. After the structure was secured, we placed a can on top of each straw. To balance the can on the straw, we placed a textbook on each side of the can (not too tightly). Carefully and gradually, we added sugar to the can for mass and recorded the mass at which the cellulose straw broke or cracked. We recorded the mass and calculated how much force destabilized the structure of the cellulose straw.

Results and Discussion

Drying Process

Once the bacterial straws have dried for two days, we could easily take out the cellulose straws from the molding source because of the vegetable we applied. However, the bacterial cellulose mold would not come off the metal and paper straws. We learned that bacterial cellulose would come off the plastic straws. This demonstrates that plastic straws can be used as an excellent and reusable molding source to create a bacterial cellulose straw.

Figure 8. Bacterial cellulose straws are attached to the paper and metal straw, making paper and metal straws an unsuccessful molding device

Flexibility

In testing the flexibility of the straws, we first began with the controls – the plastic, paper, and metal straws. As expected, the metal straw could not be bent with manual force. On the other hand, the paper straw could bend the full 180 degrees. In all three trials, however, a crease formed at the point at which the paper straw was bent, indicating a structural deformity. The paper straws readily bent at the area of the crease. The straws were subsequently bent several more times and averaged eight (8) full bends at the crease point over the three trials before a tear formed. The presence of the tear suggested that bending the paper straw caused substantial damage to the intrinsic infrastructure of the straw.

Similarly, the plastic straw was able to be bent a full 180 degrees throughout all three trials. However, a crease similar to that observed in the paper straw trials formed at the point of flexion. Continued flexion of the plastic straw at the crease was done to understand to what extent it compromised the structural integrity of the straw. Over the three trials, the plastic straw was bent on average 58 times before a tear was observed. This showed that though both plastic and paper straws are able to be bent throughout all 180 degrees, each flexion of the straws would contribute to observable damage to the structure of the straws.

The untreated cellulose straws were then tested in a similar fashion. In the first trial, the cellulose straw showed signs of tearing at approximately 160 degrees. In the second trial, the straw was bent to an angle of 175 degrees before a tear in the structure could be observed. Finally, in the third trial, the cellulose straw was bent to an angle of 169 degrees before it tore. This gives an average of 168 degrees of flexibility. In all three trials, when the straws bent past the tearing point to 180 degrees, the observed deformity increased in size. The data shows that the untreated cellulose straws are less flexible than the plastic and paper straws and more flexible than the metal straws.

In the next trials of the flexibility experiments, we tested the tung oil-treated cellulose straws. In all three trials, the tung oil cellulose straws were able to be bent the full 180 degrees without any signs of tearing. Though the flexion caused the straws to crease at the point of the bend – just as it had with the plastic and paper straws – the straws could be manually reformed with little manipulation. Doing so would make the crease disappear, and the straws could continue to be bent and reformed with no apparent damage to the structural integrity.

Finally, the linseed oil-treated cellulose straws underwent the same experimental conditions, yielding results like that of the tung oil-treated cellulose straws. In all three trials, the straws could be bent to an angle of 180 degrees without tearing. Any crease that formed could be fixed with simple remolding. This demonstrates that the oil-treated cellulose straws are just as flexible as other straw alternatives and have the added advantage of maintaining their structural integrity, a characteristic the other straw types could not achieve.

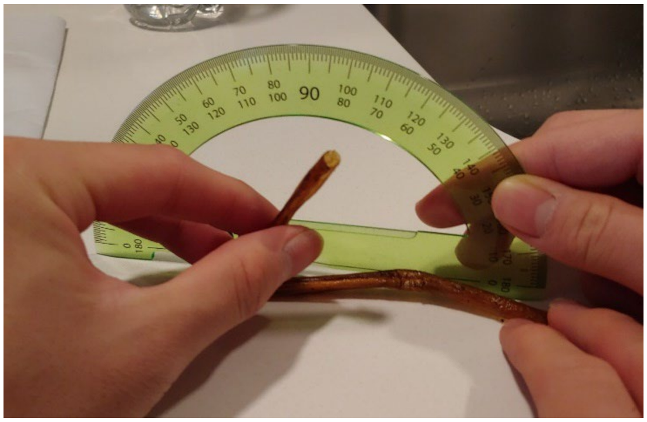

Figure 9. Our straw can bend at great lengths without any cracking or breaking

Durability of Usage

Experiments with the different straw types were run in tandem with both researchers observing. In all three trials of the metal straws, the straws showed no observable changes throughout the 30 minutes of water flowing through. Similarly, the plastic straws demonstrated a comparable performance, as no changes were seen throughout the entire duration of the experiment.

Testing the paper straws next, on average, the straws lasted 34 minutes and 42 seconds before there were signs of changes to the integrity of the straw. The straws seemed to become saturated and retain some of the water as the color of the straws became dull at around the 20-minute mark. However, they maintained their structure, and water passed through with no issue. When, on average, the 34-minute and 42-second mark was reached, the straws began to fray at the seams, and water began to leak out from those points. We deemed that the straws had lost their function and ended the experiment at that point.

In two of the three trials, the untreated cellulose straw maintained its form and kept its function throughout the entire hour. No visible changes suggest that the durability of the cellulose is high. In one of the trials, water started leaking at the seam of the straw at the 46 min 23-second mark. However, as there were no visible changes to the cellulose both at the seam and elsewhere on the straw, we concluded that this was an error in the production of the straw rather than the cellulose breaking down. We believe that we did not properly wrap the cellulose around the mold, compromising the seal and allowing water to come out of it. We repeated the experiment with a fourth untreated cellulose straw. We found that it lasted the entire hour, suggesting that the third trial was an outlier and a possible production mistake. As a result, the data for that trial was omitted.

The tung oil-treated straws and the linseed oil-treated straws demonstrated similar levels of the durability of usage as the untreated cellulose straws did. Throughout the three trials in which water was passed through the straws, neither of the types of straws had any observable differences. The color of both remained the same, and the straws did not seem to become saturated, most likely stemming from the nonpolar nature of cellulose. Additionally, the straws maintained their shape, and water did not leak through the seams throughout the one hour.

The results from these experiments indicate that - with respect to durability of usage - the cellulose straws can compete with a more popular alternatives, such as metal and plastic straws as long as the production process is without error. This is true whether or not the cellulose is treated with additives such as linseed oil and tung oil. The paper straws are a less durable alternative to plastic straws.

Tensile Strength

The tensile strength of the plastic straw was tested first. In all three trials, we found that the plastic straws would bend at the point of force at an average of 378 grams. This would form the crease that was first discussed in the flexibility experiment. However, as we increased the mass in order to increase the applied force, we found that the straw would continue to crease further but would not break. At 10000 grams, we decided that the straw would not break with the smaller amount of masses we were applying and would only bend.

In the trials with the metal straw, no amount of force applied was able to break, let alone bend the straw. The trials were concluded after the 10,000-gram mark.

The last of the controlled variables, the paper straw, was the only one of the controls to undergo a full break. Over the three trials, the amount of mass needed to break the paper straw was, on average, 9,956 grams. The paper straws would first display a sag, deviating from the midline at the point of the applied force. They would then crease and then tear apart at the point furthest from the midline. The crease first formed at an average of 5888 grams. This was always a complete tear.

The untreated cellulose straws were tested next. These straws paralleled the paper straws in that they first bent under the force and then eventually broke. However, unlike the paper straws, there was no crease in between the bending stage and the breaking stage. Throughout the three trials, the untreated cellulose straws broke at an average of 6329 grams. The break was always a full break.

The tung oil-treated cellulose straws and the linseed oil-treated cellulose straws resisted breaking up to the max mass of 10000 grams. Throughout the three trials, the tung oil-treated cellulose straws bent first, then creased at, on average, 5,989 grams. Likewise, the linseed oil-treated cellulose straws throughout the three trials bent first and then creased at, on average, 6,284 grams.

As the treated cellulose straws resisted breaking, unlike the untreated cellulose straws, this suggests that the presence of the additives increases the tensile strength of the cellulose straws and helps resist the fracture. Additionally, the treated cellulose straws were on par with the plastic straw in terms of tensile strength, as both resisted breaking. However, as the plastic straws bent at a smaller mass, this suggests that the treated cellulose straws are more resistant to stress.

Horizontal and Vertical Compression

Applying an increasing amount of horizontal and vertical compression to the metal straw through the addition of mass on the respective axes did nothing to change the form of the straw. Even at the max of 10000 grams, the metal straw maintained its shape and did not collapse.

The plastic straw collapsed on itself when horizontal compression was applied throughout all three trials. On average, this compression of the straw occurred at 209 grams. The inside of the straw would completely occlude in all three of the trials, but once the mass was removed, the straw would return to its original form. With vertical compression, we found that the plastic straw maintained its shape even at the max of 10000 grams. In one of the trials, the straw bent towards the side, but this may have been a result of not keeping the straw as vertical as possible, allowing for an applied lateral force.

The paper straw collapsed on itself when horizontal force was applied during the three trials, occluding the inside of the straw. However, unlike the plastic straw, the paper straw did not return to its original form when the mass was removed. Rather, the opening would only return to half of its original size. This horizontal compression occurred at 7688 grams over the three trials. At the max of 10000 grams, the paper straw maintained its shape during the vertical compression portion of the experiment.

The untreated cellulose straw collapsed at 1209 grams over the course of three trials. However, when the straw collapsed, it lost its shape and would not return to its original form. The straw would fracture at the point of applied force and not allow the opening to open back up again. The tung oil-treated cellulose straw compressed horizontally at 3755 grams on average, and the linseed oil-treated cellulose straw compressed horizontally at 3912 grams on average. When the horizontal force was removed for both treated straws, they were slow to return to their original forms. However, with some manipulation, both straws could be reformed, and the opening could be remade. At the max of 10000 grams, all the cellulose straws maintained their shape during the vertical compression portion of the experiment.

Table 1. Summary of the measurements of the experimental characteristics of the different straw types

	Flexibility (degrees)	**Durability of Usage (time)**	**Tensile Strength**	**Horizontal and Vertical Compression**
Metal	0	Full Duration	No break	No compression
Plastic	180	Full Duration	No break; Bend at 378 grams	H: 209 g V: No compression
Paper	180	34 min 42 sec	9956 grams	H: 7688 g V: No Compression
Cellulose	168	Full Duration	6329 grams	H: 1209 g V: No Compression
Tung oil treated cellulose	180	Full Duration	No break; Bend at 5989 grams	H: 3755 g V: No Compression
Linseed oil treated cellulose	180	Full duration	No break; Bend at 6284 grams	H: 3912 g V: No Compression

Conclusion

Through this study, different tests and comparisons of the cellulose-based straws' physical properties with that of material-based straws proved that the cellulose-based straw provided efficient flexibility, tensile strength, sturdiness, and durability. Since cellulose is a biodegradable substance compared to the polypropylene that makes up plastic straws, cellulose is safe for the environment. It would prevent the increase of climate change and other global effects. Pure bacterial cellulose can also be accessed easily by an accessible method: kombucha fermentation. Kombucha fermentation produces a great amount of bacterial cellulose from the SCOBY that can be easily made into straws with enhanced properties such as water resistance, flexibility, and a rigid structure. Even if the production of a bacterial cellulose-based straw is more feasible than other material-based straws, we've learned that kombucha fermentation requires specific conditions and specific materials to maintain the growth of cellulose properly. Through trial and error, we've experienced mold on the cellulose, dead bacterial cells, and clothes possibly contaminating the solution. Even if our study proved that cellulose-based straws are potentially more efficient in physical properties than other straws, more research and modifications should be performed on our bacterial cellulose straws for them to be successfully released into the market. Bacterial cellulose-based straws can have a wide variety of applications and can reduce the number of plastics being disposed of every day significantly because of their biodegradability and reusability.

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