

Development of Biodegradable and Antimicrobial Straws Using Edible Plant Extracts and Food-Grade Polymers

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ABSTRACT

Plastic straws are a popular item used every day, but they have created serious pollution and health risks due to not being biodegradable. To minimize plastic waste and enhance hygiene, many researchers are working on creating biodegradable antimicrobial drinking straws from edible plant extracts and food-grade polymer materials. Examples of plant extracts with bioactive (active against microbial growth) compounds consisting of phenolics, flavonoids, and curcumins include neem, turmeric, and ginger. These bioactive compounds are effective in preventing the growth of harmful microbes and thus providing a more sanitary drink. As for polymers used to manufacture biodegradable drinking straws, common examples include starch and flour; they are biodegradable, non-toxic, and environmentally friendly. When edible plant extracts are added to these biodegradable polymers during the manufacturing process, more functional properties will be achieved by providing antimicrobial properties while continuing to provide the necessary strength and flexibility of a drinking straw. To identify the functional groups and bioactive compounds responsible for their antimicrobial activity, analytical (scientific) tests using techniques such as FTIR and GC-MS will be used. In summary, biodegradable antimicrobial drinking straws, as described, provide an attractive and environmentally friendly alternative to the traditional plastic straw.

Keywords:

food grade polymer, bioactive compounds, Biodegradable Antimicrobial straw, Plant extract, Antimicrobial activity.

I. INTRODUCTION

The issue of plastic pollution is now one of the largest and most important global environmental issues due to our over-reliance on non-biodegradable materials in our daily living. Single-use plastic drinking straws are, therefore, widely used in homes, restaurants and the beverage industry as they are convenient and inexpensive to produce. These plastic straws are made from petroleum-based polymers, such as polypropylene and polystyrene, which do not break down naturally and can remain in nature for many years after they have been discarded. This large volume of plastic waste is distributed through land and water environments contributing to soil and water pollution and posing a danger to the health of humans and the stability of ecosystems. To that end, the use of sustainable alternatives must be an important focus for reducing environmental harm and enhancing ecological safety (Geyer et al., 2017).

Biodegradable products can decompose into harmless substances such as carbon dioxide, water, and biomass through the action of microorganisms. Therefore, with increases in consciousness regarding the necessity of biodegradable alternatives to synthetic plastics both biodegradable materials derived from the renewable resources of nature are receiving much attention as providing practical answers for solving plastic waste issues. Biodegradable natural polymers such as starch, cellulose and flour-based materials are viewed as viable alternatives to synthetic polymers for manufacturing straws because they are biodegradable and non-toxic. Yet, due to the moisture associated with their intended uses or the fact that they could potentially sit in storage, biodegradable materials may experience microbial contamination, thus requiring the additional incorporation of antimicrobial properties to give the straws sufficient levels of hygiene and product safety (Siracusa et al., 2018).

Plant extracts from nature provide an important resource for the development of new types of antimicrobial substances. The biochemical compounds that come from the various types of plants such as phytochemicals and others have a wide range of antimicrobial and antioxidant activity. Some examples of medicinal herbs that have been found to have therapeutic and antimicrobial activity include neem (*Azadirachta indica*), turmeric (*Curcuma longa*), and ginger (*Zingiber officinale*). Plant-derived bioactive constituents including azadirachtin, curcumin, gingerol, and shogaol, inhibit microbial growth by disrupting cellular processes and/or disrupting metabolic processes. The incorporation of plant extracts into biodegradable polymer matrices will achieve great antimicrobial efficiency while being compatible with the environment (Burt, 2004).

Biodegradable antimicrobial straws made from food-grade polymers are essential in the development process for use as food contact materials. In order to meet the criteria of biodegradable, readily available, and film-forming, the following raw materials are often utilized: starch, wheat flour, tapioca flour, gelatin and cellulose. In particular, starch-based polymers are the most commonly used material due to their affordability and renewability. Pure starches can be very brittle; therefore, plasticizers (such as glycerol) are added to the starch-based polymers to increase flexibility and strength. Additionally, incorporating natural antimicrobial extracts from plants into food-grade polymers leads to the creation of composite materials that demonstrate enhanced microbial resistance while also being environmentally responsible (Averous & Pollet, 2012).

Biodegradable antimicrobial straw production includes multiple processing steps including plant extraction; polymer blending; molding; and drying of materials used to create the straws. The plants are generally dried and subsequently powdered and extracted from a variety of sources

(e.g., solvents; e.g., water, ethanol) to produce a bioactive compound. The extracted material(s) is filtered, incorporated into polymeric mixtures using controlled heating processes to ensure uniform melting (gelatinization), molded into straw shapes, and allowed to dry to create stable mechanical straws. The mechanical properties of the straws are subsequently tested for both physicochemical and antimicrobial characteristics (Rhim et al., 2013).

Biodegradable antimicrobial straws require analytical characterization techniques to affirm their structural and functional attributes. The most utilized analytical tool for identifying functional groups and assessing interactions between polymers and plant extracts is Fourier Transform Infrared Spectroscopy (FTIR). To identify phytochemical compounds associated with antimicrobial effects, Gas Chromatography–Mass Spectrometry (GC-MS) is used. Agar well diffusion assays are also performed to determine the ability of materials to inhibit the growth of microbial pathogens, and testing is conducted on mechanical durability and water resistance (Sionkowska, 2011).

The advantages of biodegradable antimicrobial straws over traditional plastic straws include their environmentally sustainable, renewable and biodegradable nature; the use of naturally occurring antimicrobial materials to replace synthetic chemical usage; and increasing hygiene for consumers when using these straws. However, there are still challenges associated with developing the technology to make these products. For example, moisture resistance, mechanical stability, and scalability need continued research and new technology to improve performance and support commercial adoption of this biodegradable straw technology (Sharma, 2020).

The creation of biodegradable antimicrobial straws made from food-grade polymers and edible plant extracts is a new approach to solve the issues around pollutants and the safety of using plastic straws because biodegradable materials combined with natural antimicrobial agents make it possible to create both eco-friendly, and also functional alternatives for everyday usage. With more scientific research and commercialisation behind biodegradable antimicrobial straws, there is a good chance they could replace the use of conventional plastic straws in both sustainable management of the environment and the protection of public health (Gutiérrez et al., 2019).

II. NEED FOR BIODEGRADABLE ANTIMICROBIAL STRAWS

Because regular plastic straws do not break down and remain in the environment for a long time they are considered one of the major threats to Earth's ecosystem. Normal plastic straws are made using petroleum polymer which creates waste in both landfills and the ocean when they are no longer used. This type of material takes a long time to break down and creates pollution, leading to harm done to animals that eat straw that is in their environment and/or that use straws as places to live and breed. Also, improperly stored or reused straws can be carriers of bacteria and germs, which children can get sick from when they drink from them. Therefore, finding a safe sustainable, and environmentally friendly substitute for a disposable straw is essential (Geyer et al., 2017).

Biodegradable straws are a great way to solve two major problems: they eliminate plastic pollution in the world and provide consumers with an easy way to maintain hygiene when drinking liquids. They are made from natural materials—starches and flours—that will break down (biodegrade) in the environment. They are also made from 100% organic and renewable resources, i.e., they decompose due to the actions of microorganisms and do not leave behind any harmful chemicals. In addition, adding plant-derived extracts, such as neem (*Azadirachta indica*), turmeric (*Curcuma longa*), and ginger (*Zingiber officinale*), to these straws enhances their antimicrobial properties because these plants contain bioactive compounds, including phenolic compounds, flavonoids, and terpenoids, which kill the microorganisms that can grow on these straws. Thus, not only are biodegradable antimicrobial straws beneficial to the environment by reducing the amount of plastic waste in our landfills, but they are also beneficial to food and beverage safety and support environmentally friendly business practices (Burt, 2004; Siracusa et al., 2018).

III. FOOD-GRADE POLYMERS FOR STRAW DEVELOPMENT

3.1 Role of Food-Grade Polymers

Polymers that are safe to use with food can be considered food-grade. These types of polymers are important in making biodegradable antimicrobial straws because they are both non-hazardous and environmentally friendly. They come from renewable sources and have the property of breaking down naturally without leaving behind any harmful remnants. Examples of commonly-available materials used to create biodegradable antimicrobial straws are starch, cellulose, gelatin, and polylactic acid (PLA); each of these three materials has excellent properties for forming suitable solutions for use in fabricating biodegradable straws. The majority of straws manufactured today will contain starch as it is one of the most widely available, inexpensive, and easily processable natural polymers that effectively fabricate stable biodegradable structures that can be used to produce eco-friendly straws (Sharma et al., 2019).

3.2 Polymer Modification and Incorporation of Antimicrobial Agents

Food-grade polymers are often combined with plasticizers like glycerol (which can help make them less brittle and more structurally stable) in order to improve the mechanical performance and flexibility of users' products. When the addition of natural plant extracts to the polymer matrix creates a biodegradable composite material, there are several functional advantages over a traditional/non-biodegradable version. One of these is that bioactive compounds in the plant extract will provide an antimicrobial effect by inhibiting the growth of microorganisms on the finished product, thereby making the product safer when in use. Therefore, combining food-grade polymers with plant-based antimicrobial agents provides an environmentally-friendly and

effective way of producing biodegradable antimicrobial straws (Sanyang et al., 2016).

IV. ROLE OF EDIBLE PLANT EXTRACTS

Biodegradable flavours are an essential aspect to making an eco-friendly drinking straw using naturally grown plant extracts that contain anti-bacterial and anti-oxidant bioactive compounds. Many phytochemicals found in plants, including; flavonoids, phenolic compounds, alkaloids, and terpenoids exhibit anti-bacterial activity and can prevent the growth of pathogenic microorganisms. The plant materials like neem (*Azadirachta indica*), turmeric (*Curcuma longa*), and ginger (*Zingiber officinale*), derive many different medicinal and potent ingredients

including; Azadirachtin, curcumin, gingerol, shogaol which have great antibiotic and antifungal efficacy. Using edible plant extracts in licence agreements with biodegradable products contributes to improved product hygiene, additional microbial protection in the product (Kaur et al., 2017).

The use of natural sources of antimicrobial agents derived from plants can be successfully added to the production of edible films and as a way to enhance the durability and safety of biodegradable polymers, when compared to synthetic chemical preservatives. These bioactive compounds are often considered to be safe for use in relation to food products and help to provide a higher degree of protection for food by controlling the growth of pathogenic microorganisms. Furthermore, the incorporation of plant-derived antimicrobials allows for the maintenance of the biodegradability and biocompatibility of the material, and therefore, could be effectively incorporated in to sustainable packaging systems and eco-friendly straw products (Ribeiro-Santos et al., 2017)

Although they have benefits, in order to incorporate them correctly into a formula, the amount of plant extract used in that formula must be carefully monitored. Too much of an extract added into a formula can adversely affect a biodegradable product's mechanical properties, texture, color, and sensory characteristics. Therefore, finding an optimal extract concentration will help balance the antimicrobial activity and structural stability of biodegradable antimicrobial straws (Zhang et al., 2019), meaning the straws will have enough flexibility and durability to perform effectively.

V. IMPORTANCE OF BIODEGRADABLE MATERIALS

5.1 Importance of Biodegradable Materials

Renewable Natural Resources (i.e., starch, cellulose and polylactic acid) have gained significant attention as sustainable products that can be made with biodegradable materials. Unlike conventional petroleum-based plastics, biodegradable material can be biologically degraded by microorganisms to produce carbon dioxide, water and biomass, or other biologically safe products. Reducing long-term environmental pollution and accumulation of permanent plastic waste by means of the natural process (biological) of degradation of biodegradable materials helps promote environmentally responsible manufacturing processes and sustainable waste management systems (Shah et al., 2008).

5.2 Starch-Based Biodegradable Polymers for Straw Fabrication

Starch-based biodegradable materials are a popular choice for many commercial applications, such as films and packages, due to their low cost, ability to be recycled, and excellent properties for making films. Starch can be easily made into flexible shapes that can be used to make items such as disposable drinking straws. As a result of using biodegradable materials to produce straws, we are less reliant on using synthetic plastics and can provide an alternative, safer option that protects our planet and protects consumers as well (Averous & Pollet, 2012).

VI. ANALYTICAL CHARACTERIZATION

The fabrication of biodegradable antimicrobial straws requires a thorough analytical characterization to establish the specific chemical structure and compatibility of the materials being used. FTIR has been traditionally used for this purpose to determine the functional group of the biodegradable polymer and the plant extracts that were used with them. The FTIR analysis measures the molecular vibrations associated with the chemical bonds of the materials being used, thus allowing scientists to verify the interaction between the polymer matrix and the phytochemical components of the plant extract. The presence of certain functional groups (e.g., -OH, -C₆H₄-OH, and C=O groups) identified with FTIR are also believed to be important in determining the effectiveness of the biodegradable straws on antimicrobial properties and physical stability of the straws made using the materials previously described (Smith, 2011).

Gas Chromatography Mass Spectrometry (GCMS) is an advanced analytical method for identifying the active and volatile components of phytochemical plant extracts. The GCMS methodology will separate mixtures of different substances with an analytical method that can detect specific antinicotinic chemicals such as curcumin, gingerol, and azadirachtin in their respective plant materials. These chemical compounds are effective against both bacterial and fungal organisms; thus adding additional functionality to the biodegradable antimicrobial straws for developing biodegradable antimicrobial straws. GCMS provides a means to evaluate the purity of the extract, the chemical constituents within it, and the overall functional value of the product produced ensuring both safety and quality of the finalized biodegradable product (Sparkman & et al 2011).

VII. FUNCTIONAL PROPERTIES REQUIRED FOR STRAW MATERIALS

7.1 Mechanical Strength

The mechanical performance of biodegradable straws used for drinking beverages must be strong enough to resist any external force applied during manufacture or use. Most natural polymer-based materials are much less strong than traditional plastics due to the presence of attractive forces (hydrophilic) between the molecules in these materials. As a result, adequate tensile strength and rigidity must be present within the straws to hold up against breaking, bending, or collapsing from either the pressure of being submerged in a liquid or the pressure of being bitten into. The mechanical performance of biodegradable straws allows them to function correctly for the duration of their use while still maintaining a level of structural integrity comparable to that of plastics from petroleum (Sanyang et al., 2016).

7.2 Flexibility

Flexibility, another property that affects how flexible a straw can bend without breaking, will affect the strength of the straw as it bends. Many types of natural polymer types, including cellulose and starch, will dry out and create stiffer and more brittle solid films. Plasticizers, usually glycerol or sorbitol, are used to reduce intermolecular attraction between the polymeric chains and to increase the mobility of the molecules in the polymer matrix. By adding plasticizers to the polymer matrix it allows for more elasticity and prevents brittle handling of the straw after being transported or stored before being used (Rhim & Ng, 2007).

7.3 Water Resistance

The fundamental function of water-resistant drinking straws is that they will always be in contact with a liquid while they are used. Biodegradable polymers contain hydroxyl groups that readily take up moisture; therefore, these polymers are highly susceptible to absorption

of liquid moisture. Absorbing too much liquid moisture can cause the polymer to swell, soften or lose their structural integrity. One way to increase moisture penetration resistance but maintain biodegradability is to alter the composition of the polymer, use a hydrophobic component in a blend with the biodegradable polymer, or utilize controlled drying conditions (Siracusa et al., 2008).

7.4 Thermal Stability

The thermal stability of biodegradable straw materials has a significant impact on their manufacturing and real world uses. They need to withstand moderate amounts of temperature change without melting or losing their shape when being exposed to hot or cold beverages. Proper thermal resistance will provide dimensional stability while being dried, stored or consumed. Improving polymer interactions and including reinforcing agents will enhance the heat resistance of biodegradable straws and increase their functional durability (Tharathnan, 2003).

VIII. PHYTOCHEMICAL COMPONENTS RESPONSIBLE FOR ANTIMICROBIAL ACTIVITY

8.1 Phenolic Compounds

Plant-derived phenolic compounds have been identified as one of the most potent natural anti-microbial agents. The main mechanisms of action for these compounds is their ability to damage the microbial cell membrane resulting in the leaking of intracellular materials including proteins and nucleic acids. In addition to damaging the membrane, phenolic compounds also impede enzyme activity and disrupt metabolic processes of microbes. The phenolic compound curcumin, which is found within turmeric, provides the plant with strong antioxidant, antibacterial and antifungal properties. Through the induction of oxidative stress and alteration of the permeability of the microbial cell membrane, curcumin inhibits the growth of microorganisms (Cowan 1999).

8.2 Flavonoids

The antimicrobial action of flavonoids is partly due to their capacity to form complexes with the proteins located in the cell walls of microorganisms. These compounds also act as inhibitors of nucleic acid synthesis and energy metabolism within microorganisms. In a similar manner, gingerol (an important bioactive ingredient in ginger) damages the lipid components and structure of bacterial cell membranes and, therefore, prevents bacteria from colonizing. As such, the resultant damage to bacterial membranes has the effect of causing loss of cell viability and subsequently death of the microorganism (Burt 2004).

8.3 Alkaloids and Tannins

Both alkaloids and tannins are known to have strong antimicrobial activities. Alkaloids inhibit the ability of microorganisms to multiply by interfering with the replication of their DNA and the synthesis of their proteins. Tannins work by precipitating proteins from the microorganisms and forming insoluble complexes with the enzymes that are necessary for the growth of the microorganisms. The result of these actions is a reduction in the number of both bacteria and fungi found on surfaces that have been treated (Daglia, 2012).

8.4 Terpenoids

Microbial respiration and metabolic functions are inhibited by terpenoids found in neem extracts, especially azadirachtin and nimbin; when these terpenoids penetrate the cell walls of microbes they also inhibit different types of biochemical reactions that are required for the microorganisms to survive. Multiple different phytochemicals (from neem, turmeric, and ginger) produce an effective broad-spectrum antimicrobial effect through the presence of the different phytochemicals acting in synergy. This synergistic effect makes plant extracts very effective for use in developing biodegradable antimicrobial straw materials (Isman, 2006).

IX. MECHANISM OF ANTIMICROBIAL ACTION

Extracts of plants that have natural antimicrobial properties can inhibit the growth and survival of microorganisms by many different biological processes. In addition to the fact that most synthetic antimicrobial agents have a single mechanism of action, phytochemicals (compounds derived from plants) typically will have multiple mechanisms of action on several different cellular structures. The interactions include damaging the integrity of the cell membrane, inhibiting enzymes, denaturing proteins, interfering with hereditary material, and inducing reactive oxygen species; therefore it is less likely that microbes will be able to develop resistance to these types of antimicrobial agents. The multifunctional nature of these phytochemicals will be a benefit in the development of biodegradable antimicrobial straw systems that are used to provide food contact safety (Burt, 2004).

The most immediate method is through the damage of the cell membrane of the microorganism. The connection between the phenolic and terpenoid compounds found in plant extracts and the interaction of these compounds with the lipid bilayer of bacterial or fungal microorganisms leads to increased permeability of the cell membrane and a reduction in the structural integrity of the microbial cell. This will result in the leakage of intracellular constituents (ions, proteins, nucleic acids) from the microbial cell, thereby eliminating internal cellular homeostasis and ultimately resulting in cell death. This is thought to be a fast and effective method of killing microbes (Cowan, 1999).

An important part of how chemicals kill microbes is by hindering the function of enzymes. Bioactive phytochemicals can impede

the function of certain enzymes in microbes that are used for metabolic activity such as respiration and using nutrients. For example, some flavonoids and alkaloids bind to the active sites on enzymes so those enzymes cannot carry out their normal biochemical processes inside the microbial cell. When certain enzymes are inhibited, the microbe's ability to produce energy and to make the necessary metabolic processes needed for life is disrupted and thus the reproduction and growth is inhibited (Daglia, 2012).

In addition to enzyme inhibition, many natural antimicrobial agents also denature protein and cause damage to microbial structural elements. Tannins and phenolic compounds bind with microbial proteins via the formation of noncovalent protein–redox complexes, which change the three-dimensional (3D) conformation and/or biological function of the protein. The denaturation of microbial proteins affects both membrane proteins and intracellular enzymes involved with cellular regulation, so the microbial cells no longer have physiological activity and are rendered nonviable (Sikkema et al., 1995).

Numerous botanically derived phytochemical compounds can act as agents of oxidative stress by creating (ROS) within the cells of microorganisms. The overproduction of ROS is capable of damaging the entire cell structure, including, but not limited to, DNA, lipids and proteins, by way of oxidation. This oxidative imbalance is so great that it overwhelms the natural cell protection mechanisms of microorganisms, resulting in the increase of cellular destruction. Antimicrobial phytochemicals yeast/water are combined with curcumin and gingerol, both considered to be able to increase oxidative damage to pathogenic microorganisms (Burt, 2004)

As a result of combining cytopathic effects with metabolic inhibition, damage to cellular proteins and the generation of oxidative stress, the overall result is a broad range of antimicrobial action. When used in biodegradable straws, these various mechanisms work together to be able to help protect the sterility of the straw surfaces, thereby increasing cleanliness, improving the safety of the straws for use in food contact applications and reducing the overall shelf life of such product.

X. COMPATIBILITY BETWEEN POLYMERS AND PLANT EXTRACTS

10.1 Importance of Polymer–Extract Compatibility

One of the keys to successfully fabricating biodegradable antimicrobial materials is ensuring that the polymer matrix is compatible with the incorporated plant extracts. Compatibility is defined as how uniformly the bioactive compounds derived from plants will disperse throughout the polymer structure without causing separation or destabilizing the structure. When developing biodegradable straws, if there are incompatible interactions between polymers and plant extracts, this could lead to poor mechanical properties of the product, an irritatingly uneven performance of the antimicrobial properties, or weeks in durability. Consequently, achieving compatibility at a molecular level is critical for producing stable and functional antimicrobial composite materials (Rhim et al., 2013).

10.2 Intermolecular Interactions Between Polymers and Phytochemicals

Intermolecular interaction formation is an important factor in determining compatibility. Hydrogen bonding between functional groups of polymers and phytochemicals in plant extracts is a particularly important form of intermolecular interaction that affects compatibility. Hydroxyl groups within biopolymers (i.e., starch, cellulose, and carboxymethyl cellulose) allow for interactions with phenolic and flavonoid compounds within extracts of plants (i.e., neem, turmeric, and ginger). These hydrogen bonds provide an additional means for enhancing adhesion between polymer components and distributing antimicrobial agents throughout the polymer matrix in a homogeneous manner (Tharanathan, 2003).

10.3 Uniform Dispersion of Bioactive Compounds

Good compatibility enhances the distribution of plant-based extracts in the polymer matrix during the production of biodegradable straws, which means they are more likely to be evenly dispersed, therefore less likely to aggregate or cluster during production, which could lead to weak points in the physical structure of the material. The homogeneous spread of plant-based extracts in the polymer matrix will ensure that there is consistent antimicrobial activity across the entire surface of the biodegradable straw.

10.4 Influence on Mechanical Stability

The mechanical stability of the developed composites is strongly influenced by the compatibility of the polymers and the plant extracts. A well-integrated composite system will have the desired properties of tensile strength, flexibility, and surface smoothness. Furthermore, through this balanced compatibility, the addition of plant extracts has no negative effects on the performance of straw in real-world use (Rhim & Ng, 2007).

10.5 Controlled Release of Antimicrobial Compounds

Compatibility is an important factor in controlling how antimicrobial substances are released from the polymer matrix. When phytochemicals are correctly incorporated in the polymer matrix, the active molecules will be released continuously onto the surface of the material to provide long-term antimicrobial effects. If the compatibility of the phytochemicals is poor, this will lead to rapid leaching of the active substances from the polymer, which will reduce their effectiveness (Sanyang et al., 2016).

10.6 Prevention of Phase Separation and Structural Defects

Polymer-extract combinations that are compatible will help prevent the occurrence of phase separation during the fabrication, drying, and storage of these items. Components of a composite will separate into different phases if they are not compatible, causing cracks within the material, as well as non-uniform texture and reduced durability. The strong molecular interactions between all the contributing components of a composite material will stabilize its overall structure and allow for a consistent antimicrobial effect over the entire length of the straw (Rhim et al., 2013).

10.7 Overall Impact on Functional Performance

The development of straw-like materials containing biodegradable polymers in combination with plant extracts will enhance their mechanical properties, physical stability, antimicrobial activity, and longevity. Ensuring compatibility between these components through optimization will allow the manufacture of environmentally friendly and functional biocidal biodegradable straws for food packaging and commercial use.

XI. CONCLUSION

Biodegradable antimicrobial drinking straws have been created from plant-based materials and food-safe polymers. These straws offer a solution to both environmental pollution and disease-causing bacteria. The use of biodegradable polymers offers the bioproducts' biodegradable nature, while the phytochemicals that can be derived from these consumers' will protect against bacteria. Future research and advances in technology will enable more companies to sell environmentally safe drinking straw alternatives than ever.

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