AReviewonEdiblePackagingand

EdibleStraws

# ABSTRACT

Plastic pollution is among the most urgent environmental crises of the 21st century, with single-use plastic strawscontributingsignificantlytomarinelitterandmicroplasticcontamination.Inlightofgrowingenvironmental awareness and international policy efforts to reduce plastic consumption, edible straws have emerged as a promisingbiodegradablealternative.Thisreviewcriticallysynthesizesfindingsfrom32Scopus-indexedstudies published between 2020 and 2025, focusing on the latest developments in materials, fabrication methods, mechanical performance, environmental sustainability, and consumer perception related to edible straw technologies.

Ediblestrawsaretypicallymadefromrenewable,food-gradebiopolymerssuchasstarch(cassava,corn,rice), seaweed polysaccharides (agar, alginate, carrageenan), cellulose (derived from agricultural waste), and proteins(soy,whey,gelatin).Thesematerials offerinherentbiodegradabilityand aregenerallysafeforhuman consumption. Functional additives like plasticizers (glycerol, sorbitol) and hydrophobic coatings (beeswax, shellac)enhanceflexibilityandwaterresistance.Amongthematerialsreviewed,cellulose-basedstrawsexhibit the highest tensile strength and durability in beverage immersion, while protein- and seaweed-based straws offer superior sensory qualities and faster degradation profiles.

Despite their environmental benefits such as lower carbon emissions and rapid compostability edible straws faceseveralcommercialbarriers,includinghighproductioncosts,shortshelflife,variablematerialperformance, and a lack of unified regulatory standards. Life cycle assessments confirm their ecological superiority over plastic and paper alternatives, yet widespread adoption is hindered by cost sensitivities and limited consumer familiarity.

Emerging solutions involve hybrid biopolymer systems, nanomaterial reinforcements, and scalable fabrication techniques like co-extrusion and 3D printing. Additionally, flavor customization and user-centered design can improveconsumeracceptance.Forediblestrawstotransitionfromnicheinnovationtomainstreamapplication, coordinated efforts across materials science, food engineering, regulation, and public engagement are essential.

**Keywords:***Ediblepackaging,Ediblestraws,Biodegradableutensils,Seaweedbioplastics,Starch-based films, Sustainable packaging, Consumer acceptance, Food-grade materials*

## INTRODUCTION

The increasing environmental concerns arising from the excessive use of synthetic, petroleum- basedplasticshavesparkedglobaleffortstofind sustainable, biodegradable, and eco-friendly alternatives in food packaging. Among various categoriesofbiopolymersandgreeninnovations, edible packaging has gained considerable attention due to its unique ability to be safely consumedalongwiththefoodproductitprotects, thereby eliminating waste entirely (Han, 2014). Edible packaging is developed using biodegradable polymers such as proteins, polysaccharides, and lipids, often combined with plasticizers, cross-linkers, or bioactive compounds to enhance mechanical, barrier, and functional properties (Wu et al., 2024; Kumar et al., 2022).

As an important subset of edible packaging, edible straws have emerged as a promising solution to the environmental hazards posed by single-use plastic straws. Plastic straws are among the most common marine pollutants, and their slowdegradationtime—estimatedat300 to 500 years—makes them a significant contributor to white pollution (Putri and Falah, 2022). While alternatives like paper or plant-based straws exist, they often lack water resistance and structuraldurability(Djekicetal.,2024;Timshina et al., 2021). As such, edible straws—produced from materials like starch, seaweed, cellulose, soy protein, and rice bran—are being actively researched for their biodegradability, functionality,andconsumeracceptability(Patilet al., 2025; Kajla et al., 2024).

Ediblepackagingmaterials relyheavilyonnatural polymers,primarilypolysaccharides andproteins, which are generally recognized as safe (GRAS), renewable, and cost-effective. Starch, a polysaccharide widely available from rice, corn, and potatoes, is extensively used for fabricating edible straws. The extrusion–retrogradation methodhassignificantlyimprovedthemechanical strength and hydrostability of corn starch-based straws, making them viable substitutes for commercial plastic straws (Cui et al., 2023). The addition of cross-linking agents such as sodium trimetaphosphate (STMP) has been shown to further enhance the mechanical integrity and thermal resistance of starch-based straws (He et

al., 2023). Furthermore, blending starch with polyvinyl alcohol (PVA) enhances hydrogen bondinginteractions, resulting inimprovedtensile strength and water resistance (Wei et al., 2023).

In addition to starch, cellulose—particularly in its nanocellulose and bacterial cellulose forms—is gaining traction as a straw base due to its high tensile strength, superhydrophobicity, and biodegradability. Cellulose-based straws inspired by natural surfaces like sugarcane peel can achieve remarkable tensile strength and wet durability through surface modification using natural fatty acids (Qin et al., 2022). Other innovationsutilizebacterialcellulosemodifiedwith soy protein and calcium alginate to produce low- hygroscopic, edible films with oil resistance and excellentopticalclarity(Cheungetal.,2023).The valorizationofagro-waste,suchasricestraw,has also enabled the production of nanocellulose materials for sustainable food packaging, thus closing the agricultural waste loop (Islam et al., 2023).

Among marine biopolymers, seaweed-derived polysaccharides have emerged as attractive candidates due to their intrinsic film-forming abilities, biodegradability, and bioactivity. Seaweed-based packaging has been reported to offer antioxidant and antimicrobial properties but suffers from limitations such as high water solubility and low tensile strength. These shortcomings can be mitigated through nanoparticle reinforcement or blending with other biopolymers (Kajla et al., 2024). For instance, seaweed-derived cellulose fibers and soluble polysaccharides can be combined through Ca2+ chelation and freeze-thawing to yield straws with highwaterstabilityandstructuralresilience,which can even incorporate natural pigments for freshnessindicationinbeverages(Nietal.,2024).

Protein-based edible straws, using ingredients like gelatin, whey protein isolate, and soy protein, offer promising mechanical performance but face challenges like water sensitivity and allergenicity. Crosslinking gelatin with delignified, phosphorylated bamboo scaffolds has resulted in straws with high stiffness, hydrophobicity, and excellent biodegradability, validated by life-cycle assessments (Rai et al., 2023). Similarly, soy protein isolate blended with cassava starch and coated with natural waxessuchasbeeswaxandshellachas

demonstrated significant improvements in mechanical durability and water resistance, allowing functionality over extended periods in beverages (Choeybundit et al., 2024).

The integration of functional ingredients, such as natural pigments and antimicrobial agents, is pushing the boundaries of edible packaging into the realm of smart packaging. Cellulose-based hydrogels infused with natural colorants can be used to detect spoilage or pH changes in food and beverages, thereby enhancing food safety (Yang et al., 2024). Periwinkle extract, a bioactive compound with proven antimicrobial properties, has also been incorporated into starch films to create packaging materials that inhibit bacterial growth while being biodegradable (Samiha et al., 2025).

From a consumer standpoint, the success of edible packagingreliesnotonlyontechnicalperformancebut also on acceptability, sensory perception, and usability. For instance, Generation Z consumers preferred paper straws that didn’t affect flavor or dissolve too quickly, but noted issues with firmness and shape retention in moist conditions (Djekic et al., 2024). This highlights the importance of balancing sustainability with functional and sensory properties. Studies also emphasize the need for uniform evaluationcriteriatoassessthecompatibilityofedible straws with different beverages (Patil et al., 2025).

Safety and regulatory considerations are another important dimension. While edible straws reduce dependency on non-renewable resources, the presence of chemical contaminants like per- and polyfluoroalkyl substances (PFAS) in some plant- based straws raises concerns. Research has shown that PFAS can leach into beverages, thereby defeating thevery purpose of offeringa clean, green alternative(Timshinaetal.,2021).Hence,developing standardized methods for chemical testing and certifications is vital.

Recent reviews emphasize the need for composite materials to overcome the drawbacks of single- component systems. Composite edible films using blends of pectin, alginate, and whey protein have demonstrated improved barrier, optical, and mechanical characteristics (Chakravartula et al., 2019). The use of plasticizers like glycerol and sorbitol has also shown to enhance film flexibility, although their concentration must be carefully optimizedtomaintainbalancebetweenwater

permeability,strength,andbiodegradation(Sanyang et al., 2016; Liu et al., 2025).

In conclusion, edible packaging particularly edible straws—represents a crucial innovation toward reducing plastic waste and achieving a circular bioeconomy. Progress in material science, processing technologies, and consumer engagement continues to push the boundaries of what edible straws can achieve. However, challenges remain in terms of scalability, regulatory compliance, and real- world performance. Future research should focus on developing multifunctional, economically viable, and socially acceptable ediblepackagingsystemsthatserveasgenuine replacements for traditional plastics.

# MATERIALSFOREDIBLESTRAW FABRICATION

* 1. **Starch**

Starch is one of the most widely used biopolymersinediblestrawproductionduetoits availability, biodegradability, and excellent film- forming ability. It is derived from various botanicalsourcessuchascorn,rice,potato,and cassava, offering cost-effective options for large-scale production (Han, 2014). However, native starch presents limitations such as poor mechanical properties and water sensitivity, whichoftennecessitatemodificationorblending with other substances.

A notable advancement in starch-based straw fabrication involves the use of extrusion and retrogradation techniques to enhance structural stability. Cui et al. (2023) developed corn starch strawswithstrongmechanicalpropertiesthrough optimized extrusion and retrogradation, resulting in improved strength and reduced solubility. In a complementarystudy,Heetal.(2023)employed a combined approach involving extrusion, retrogradation, and cross-linking to further improve water resistance and mechanical integrity of starch-based straws. These process modifications ensure the material remains functional in liquid environments without disintegrating quickly.

Plasticizerssuchasglycerolandpolyvinylalcohol

(PVA) are also frequently incorporated to improve flexibility and toughness. Liuetal.(2025)investigated the effect of water and glycerol ratios on starch-based straws and found that the correct balance enhances elasticity without compromising biodegradability. Similarly, Wei et al. (2023) explored intermolecular interactions between starch and PVA, highlighting how hydrogen bonding significantly reinforces the straw’s mechanical properties and dimensional stability.

Moreover, regional studies, such as that by Putriand Falah (2022), have demonstrated the feasibility of utilizing agricultural waste, like unused rice and rice bran, for starch-based straw development. Their work underscores the potential of valorizing local byproducts in eco-friendly packaging applications. Yavagal et al. (2020) also promoted cleaner production of edible straws from sugar palm starch, emphasizing its potential as a replacement for thermoset plastic materials.

Despite these advances, starch-based straws still face challenges with prolonged exposure to liquids, especially hot beverages. Yet, ongoing research and innovative processing techniques continue to mitigate these issues, making starch a promising material in edible straw manufacturing (Patil et al., 2025; Liu et al., 2024).

## Cellulose

Cellulose, the most abundant natural polymer on Earth, is another prominent material used in edible straw production due to its excellent tensile strength, chemical resistance, and biodegradability. As a structural polysaccharide, cellulose can be derived from plant fibers, bacterial biosynthesis, or agro- industrial residues, each offering unique benefits (Han, 2014; Islam et al., 2023).

Qin et al. (2022) developed a bioinspired, strong, all- natural cellulose-based straw with super hydrophobic properties by mimicking the surface structure of sugarcane peels and modifying them with natural fatty acids.This innovation resulted in straws that are not only edible and degradable but also water- repellent, which significantly enhances usability in liquid environments.

Bacterial cellulose has also been explored for its low hygroscopicity and high mechanical strength. Cheung et al.(2023)reported the development of

bacterial cellulose-based materials enhanced through biosynthesis and physical modification. These materials produced edible straws with superior structural integrity and oil resistance, ideal for both dry and wet applications.

In a broader environmental context, Islam et al. (2023) reviewed the use of rice straw for nanocellulose production, highlighting its potential as a sustainable raw material for food packaging. Similarly, Ni et al. (2024) created edible, hydrostable straws using a combination of seaweed-derived insoluble cellulose fibers and soluble polysaccharides. Their freeze-thaw technique resulted in highly durable and water- resistant products, suitable for long-term beverage contact.

Yang et al. (2024) further emphasized the use of cellulose hydrogels in smart packaging applications. By incorporating natural pigments into cellulose-based matrices, they produced responsive packaging capable of indicating spoilage or pH changes. This smart functionality extends the value of cellulose-based materials beyond structural support, adding real-time food safety indicators to their utility.

Collectively, these innovations position cellulose as a versatile material for edible straws, especially when enhanced through physical or chemical modifications and paired with sustainability-driven sourcing.

## Seaweed

Seaweed-derived polysaccharides such as agar, alginate, and carrageenan have garnered attention in edible straw development due to their gelling properties, film-forming ability, and inherent biodegradability. Seaweed is a renewable marine biomass that grows rapidly without the need for fresh water, fertilizers, or arable land, making it an eco-efficient material choice (Kajla et al., 2024).

Seaweed-based biopolymers often exhibit favorable antioxidant and antimicrobial properties, but their high water solubility and relatively low mechanical strength pose processing challenges (Kajla et al., 2024). These limitations can be overcome through the use of blending agents or structural enhancers. Ni et al. (2024) addressed these issues by integrating seaweed-derived

insoluble cellulose fibers with soluble polysaccharides, followed by freeze-thaw stabilization. The resulting straws displayed enhanced hydrostability and structural resilience while remaining edible and biodegradable.

Kajla et al. (2024) also highlighted various reinforcement strategies for seaweed-based packaging, such as nanomaterial incorporation, multilayered structures, and bioactive agents, which can improve both performance and shelf- life. These adaptations make seaweed a competitive material for edible straws, especially in contexts where marine-derived ingredients are locally abundant or culturally relevant.

Seaweed-based solutions align well with the circular economy model and low-carbon manufacturing approaches, making them highly attractive for sustainable packaging applications (Roy et al., 2021).

## Proteins and Composites

Protein-based materials, such as gelatin, soy protein isolate, and whey protein, are increasingly used in edible packaging for their excellent film-forming, biodegradable, and edible properties. These materials provide elasticity and barrier properties, but they are generally sensitive to moisture and temperature (Han, 2014; Wu et al., 2024).

Rai et al. (2023) developed composite straws using delignified and phosphorylated bamboo- gelatin blends. The resulting material demonstrated strong mechanical properties, water resistance, and biodegradability, confirmed through life cycle assessments. This innovative composite approach leverages both natural protein functionality and structural support from lignocellulosic biomass.

Similarly, Choeybundit et al. (2024) produced eco-friendly straws by blending soy protein isolate with cassava starch and coating the composite with bees wax and shellac. This dual- layer structure improved water resistance while maintaining flexibility and edibility. The protein-polysaccharide synergy in such composites balances the mechanical shortcomings of pure protein films with the structural strength of polysaccharides.

Chakravartula et al. (2019) reported success in combining pectin, alginate, and whey protein concentrate to create composite edible films with improved barrier and mechanical properties, suggesting similar strategies could be adopted in straw manufacturing.

The inclusion of plant-based or animal-derived proteins enhances the nutritional profile of edible packaging, although allergenicity and regulatory concerns must be addressed. Nevertheless, protein-based and composite materials offer a functional and customizable platform for next- generation edible straws.

Table1: Comparison of edible straw materials

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Material Type** | **Sources** | **Key Properties** | **Strengths** | **Limitations** |
| **Starch** | Corn, rice, cassava starch (Cui et al., 2023;Heetal.,2023;Putri&Falah,2022) | Biodegradable, good film-forming, water sensitive, improved byRetrogradation and plasticizers | Low cost, good filmability, edible, scalable(Han,2014; Liu et al., 2025) | Poor water resistance, brittle without additives (Patil et al., 2025) |
| **Cellulose** | Plant fibers, bacterial cellulose, rice straw (Qin et al., 2022; Cheungetal.,2023; Islam et al., 2023) | Strong, hydrophobic when modified, low hygroscopicity, renewable | Excellent strength, structure retention, environmentally friendly(Yangetal., 2024) | Processing complexity, sometimes brittle(Islam et al., 2023) |
| **Seaweed** | Seaweed polysaccharides: agar, alginate, carrageenan (Kajla et al., 2024; Ni et al., 2024) | Fast-growing, biodegradable, water- soluble unless modified | Marine biomass, antimicrobial potential, renewable (Kajla et al., 2024) | Low mechanical strength, high water sensitivity (Nietal., 2024) |
| **Proteins &Composites** | Gelatin, soy protein isolate, whey protein (Rai et al., 2023; Choeybundit et al., 2024;Chakravartulaetal.,2019) | Elastic, edible, biodegradable, sensitive to moisture, improved in composites | Nutritional value, biodegradable, flexible(Wu et al., 2024) | Moisture sensitive, possible allergenicity (Han, 2014) |

# FABRICATION AND PROCESSING TECHNIQUES

The advancement of edible straws as a sustainable alternative to conventional plastic- based products has prompted extensive exploration into diverse fabrication techniques. These techniques are pivotal in determining not only the mechanical robustness and biodegradability of the final product but also its interaction with moisture, flavor retention, and shelf stability. This chapter discusses the principal fabrication strategies used in the development of edible straws, specifically focusing on processing routes involving starch, cellulose, seaweed, and protein-based materials.

## Extrusion Technology

Extrusion is one of the most extensively employed techniques in edible straw fabrication, particularly for starch-based formulations. Cui et al. (2023) demonstrated that extrusion followed by retrogradation enhanced the mechanical strength and water resistance of corn starch- based straws. Similarly, He et al. (2023) introduced a combined strategy of extrusion, retrogradation, and cross-linking to achieve

straws with improved dimensional stability and tensile strength.

## Retrogradation and Annealing

Retrogradation, often used post-extrusion, involves the reorganization of starch molecules, which strengthens the internal matrix. It is effective in reducing solubility and enhancing the mechanical integrity of starch products. As He et al. (2023) and Wei et al. (2023) showed, retrograded starch matrices displayed superior resistance to cracking and degradation in aqueous environments.

## Cross linking and Reinforcement

Cross linking agents, such as citric acid or polyvinyl alcohol (PVA), can be added to improve the structural coherence of biopolymer matrices. Wei et al. (2023) examined intermolecular interactions between starch and PVA, reporting enhanced flexibility and durability. Cross linking also plays a role in reinforcing protein and cellulose matrices, as discussed by Rai et al. (2023) in their bamboo- gelatin composite straw fabrication process.

## Casting and Coating Techniques

Casting is widely applied for forming thin films or

coatings from biopolymer dispersions. Choeybundit et al. (2024) fabricated protein- starch straws using a fusion of soy protein isolate and cassava starch, followed by coating with bees wax and shellac to reduce moisture permeability. This multilayered structure improved the barrier properties of the straw. Han (2014) also outlined the advantages of casting in producing smooth, homogenous films with controlled thickness.

## Composite and Hybrid Processing

Composites integrate multiple biopolymers to harness their combined properties. For instance, Chakravartula et al. (2019) developed pectin- alginate-whey protein edible films through controlled heating and solution blending. This approach not only strengthened the films but also improved their functional and sensory attributes. Similar hybrid systems have been employed using cellulose fibers, starch, and gelatin for eco-friendly straw production(Kajla et al., 2024; Qin et al., 2022).

## Additive Integration: Plasticizers and Natural Agents

Plasticizers like glycerol and sorbitol are vital for improving the flexibility of starch and protein- based films. Liu et al. (2025) investigated the impact of varying glycerol-water ratios, concluding that optimized ratios significantly influence the physicochemical properties of straws. Moreover, natural additives like periwinkle extract (Samiha et al., 2025) and paprika-derived phytochemicals (Kim et al., 2011) have been used to enhance antimicrobial and antioxidant properties.

## Influence of Processing on Functional and Mechanical Properties

Processing parameters, such as temperature, shear rate, and drying time, critically influence the straw's functionality. As described by Han (2014), high-temperature processing can improve crystallinity in starch films, enhancing tensile properties but potentially reducing solubility. Liu et al. (2024) and Ni et al. (2024) highlighted that cellulose and seaweed-based films require precise moisture control to avoid

Warping and swelling.

## Challenges in Scale-Up and Standardization

Despite technological progress, challenges persist in scaling up edible straw production while maintaining quality and consistency. Roy etal.(2021) and Patil et al. (2025)reported that commercial production is hindered by variability in raw materials and the need for optimized multi-step processing. Furthermore, Timshina et al. (2021) emphasized the importance of ensuring the absence of contaminants like PFAS during fabrication, especially in commercially marketed plant-based straws.

## FUNCTIONAL AND PHYSICOCHEMICAL PROPERTIES

The development of edible straws as a sustainable alternative to plastic straws necessitates a comprehensive understanding of their functional and physicochemical properties. These properties determine the straws’ usability, performance in various environmental conditions, and acceptability in food and beverage applications. Key parameters include mechanical strength, water solubility, biodegradability, barrier characteristics, flexibility, thermal stability, and sensory compatibility. This chapter evaluates the performance of starch, cellulose, seaweed, and protein-based straws using empirical insights and reviews from recent literature.

## Mechanical Properties and Structural Integrity

Mechanical strength is a critical factor, especially when edible straws are used in hot or cold beverages. According to Cui et al. (2023), starch- based straws developed through extrusion and retrogradation processes exhibited improved tensile strength and reduced breakage compared to non-retrograded formulations. The combination of retrogradation and extrusion allowed molecular reorganization of amylose and amylopectin chains, contributing to a denser and more durable internal matrix. He et al. (2023) further enhanced these properties using cross linking, enabling straws to resist deformation under hydration stress.

Similarly, Ni et al. (2024) developed seaweed- based straws that retained structural integrity in

Liquid for over 24hours due to a dual-component system of insoluble cellulose fibers and soluble polysaccharides. These fibers served as a reinforcing phase, forming a web-like network within the matrix. Qin et al. (2022) also reported high tensile strength in cellulose-based straws, especially after surface treatment to impart hydrophobicity and reduce capillary absorption of water.

## Water Solubility and Swelling Behavior

Edible straws are inherently hydrophilic due to their polysaccharide-rich composition, which often leads to undesirable swelling or disintegration when exposed to aqueous media. To counter this, fabrication processes incorporate retrogradation, cross linking, and coatings. Wei et al. (2023) investigated intermolecular interactions between starch and polyvinyl alcohol (PVA), revealing a significant reduction in solubility and an increase in water resistance. Liu et al.(2025)found that optimized glycerol-to-water ratios reduced the hydrophilic nature of starch-based straws, minimizing early- stage swelling.

Seaweed-based straws demonstrated varied hydration behavior depending on the seaweed species and cross linking degree. Ni et al.(2024) showed that alginate- and carrageenan-based systems swell quickly, but their mechanical resilience depends on fiber integration and crosslink density. Han (2014) emphasized that the water resistance of edible coatings can be improved by incorporating waxes or lipid emulsions, as practiced in composite straws like those by Choeybundit et al. (2024), who coated soy protein and starch composites with beeswax and shellac.

## Thermal Stability and Heat Resistance

Thermal stability is crucial for withstanding hot beverages. He et al. (2023) confirmed that cross-linked starch films displayed increased glass transition temperatures, correlating with improved thermal endurance. Rai et al. (2023) also noted that bamboo-gelatin composites with phosphorylated treatment were able to maintain shape and performance in hot liquids. Proteins typically have lower thermal resistance than polysaccharides; however, when blended with

fibrous cellulose or starch, the combined matrix performs better thermally.

In their review, Liu et al. (2024) highlighted the importance of selecting thermally stable additives during fabrication. For example, curdlan, a microbial polysaccharide, improves the gelation temperature of protein matrices, as explored by Hu et al. (2024). When used with whey protein isolate, curdlan enhanced thermal resistance and mechanical gel strength.

## Barrier Properties (Gas and Moisture)

Barrier properties determine the functional application of straws in sealing or serving beverages. Patil et al. (2025) emphasized the need for balance between oxygen permeability and water vapor transmission rates in edible straws. High barrier performance is especially essential for beverage applications that require extended immersion. Choeybundit et al. (2024) effectively reduced moisture permeability using beeswax coatings, while Chakravartula et al. (2019) demonstrated that pectin-alginate- protein films can regulate oxygen and carbon dioxide permeability through ionic cross linking.

Qin et al. (2022) used plasma treatment on cellulose to create a super hydrophobic surface, achieving very low water vapor permeability. Ni et al. (2024) also confirmed enhanced barrier function in seaweed-based straws due to their fiber-rich outer layer.

## Biodegradability and Edibility

As per Roy et al. (2021), the true ecological benefit of edible straws lies in their complete biodegradability and potential edibility. Most starch, cellulose, and protein-based straws are compostable within a few weeks in natural environments. Islam et al. (2023) reported that nanocellulose derived from rice straw is not only biodegradable but also enhances microbial degradation when used in packaging. Edibility, on the otherhand, requires non-toxic ingredients and absence of synthetic additives. Han (2014) provided a comprehensive review of GRAS- status biopolymers and additives that ensure edibility.

Rai et al. (2023) and Gupta et al. (2024) emphasized that gelatin and soy-protein-based

straws are fully digestible and pose no risk if consumed accidentally. However, Timshina et al. (2021) issued caution on commercially available straws containing PFAS, stressing the importance of verifying food safety compliance.

## Optical, Sensory, and Aesthetic Properties

Wu et al. (2024) discussed the aesthetic parameters of edible packaging films, such as transparency, gloss, and coloration, which significantly influence consumer acceptance. In straws, natural colorants like fruit or spice extracts (e.g.,paprika from Kim et al.,2011)are used to improve appearance and provide antioxidant benefits. Yang et al. (2024) introduced smart cellulose hydro gels with embedded natural colorants that change hues with pH—offering potential applications in beverage pH monitoring.

Choeybundit et al. (2024) also highlighted that protein-based straws could be made visually appealing and flavorful without compromising structural integrity. The fusion of functionality and aesthetics opens avenues for customized edible straws with marketable advantages.

## Compatibility with Beverages and Sensory Performance

Functional compatibility with a variety of beverages, including acidic, carbonated, and hot drinks, is crucial. Yavagal et al. (2020) reported that rice starch-based straws retained shape and function for up to 30 minutes in carbonated drinks, whereas gelatin-based versions were more suitable for milkshakes or smoothies. Djekic et al. (2024) examined Generation Z preferences and found that consumers were more likely to reuse straws with neutral or sweet flavor tones.

Sensory properties like mouthfeel, taste, and aroma must be carefully tuned. Han (2014) emphasized that flavor migration from the straw to the beverage must be minimal unless intentional. Chakravartula et al. (2019) highlighted that pectin-protein blends possess a neutral taste and smooth texture, preferred for direct contact applications.

## Influence of Processing on Physicochemical Traits

Processing conditions influence multiple functional properties. Liu et al. (2025) demonstrated that changing water and plasticizer ratios significantly alters surface roughness, water activity, and moisture retention. Similarly, Kajla et al.(2024) observed that seaweed film properties varied depending on the biopolymer extraction process, affecting thickness, density, and biodegradability.

Agumba et al. (2023) developed thermoset- derived microplastic-free films that were hydrostable and ultra-strong, suitable for high- performance straws. However, their thermal curing process requires energy-intensive steps, which can limit widespread application.

To comprehensively assess the suitability of different biopolymers for edible straw production, it is essential to compare their key functional and physicochemical characteristics. Table 2 presents a structured comparison of four major categories of materials commonly used in edible straw fabrication: starch, cellulose, seaweed-derived polymers, and protein-based composites. The comparison includes critical parameters such as mechanical strength, flexibility, water stability, biodegradability, and edibility—each of which directly impacts straw performance in beverage applications, user safety, environmental sustainability, and consumer acceptance.

This tabular summary is based on peer- reviewed scientific literature and aims to provide a clear, evidence-backed perspective on the strengths and limitations of each material type. The table serves as a practical reference for researchers, developers, and stakeholders in the food packaging industry to make informed decisions when designing or evaluating edible straw formulations.

Table2: Comparative Analysis of Materials Used in Edible Straws

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Material Type** | **Mechanical Strength** | **Flexibility** | **Water Stability** | **Biodegradability** | **Edibility** | **References** |
| Starch | Moderate to High (improved via extrusion, retrogradation) | High with plasticizers | Low to Moderate; improved with PVA or glycerol | Fully biodegradable | Edible | Cui et al., 2023; He et al., 2023; Wei et al.,2023; Liu et al.,2025; Patil et al., 2025; Han, 2014 |
| Cellulose | High (especially after surface modification or fiber addition) | Moderate | High water resistance, especially with hydrophobic treatments | Biodegradable and compostable | Edible (plant/bacterial origin) | Qin et al., 2022; Cheung et al., 2023; Yang et al.,2024; Ni et al., 2024 |
| Seaweed | Moderate; reinforced by insoluble fibers | Moderate | Moderate to High, depending on formulation and cross linking | High biodegradability | Edible(alginate, carrageenan) | Ni et al.,2024;Kajla et al.,2024; Han, 2014 |
| Proteins &Composites | Moderate to High (gelatin or soy isolate- based) | High; tunable with plasticizers/wax | Variable; improved with beeswax/shellac coatings | Edible and biodegradable | Fully edible (GRAS proteins) | Rai et al.,2023; Choeybundit et al., 2024; Chakravartula et al., 2019; Wu et al., 2024; Han,2014 |

The comparative analysis in Table 2 underscores the varying strengths and limitations of each material used in edible straw fabrication. Starch is widely favored for its availability, cost-effectiveness, and edibility, although its water sensitivity requires modification through plasticizers or cross linking. Cellulose offers excellent mechanical strength and water resistance, making it suitable for demanding applications, but often involves more complex processing. Seaweed-based materials an eco-friendly option with good biodegradability, though they typically need reinforcement to improve mechanical stability. Protein-based composites provide notable flexibility and sensory appeal, but may suffer from moisture sensitivity and require careful formulation to avoid allergenicity. Overall, the data indicate that no single material satisfies all performance criteria, highlighting the potential of multi- component blends—such as starch–cellulose–protein combinations—to deliver balanced functionality, consumer acceptability, and environmental sustainability.

## Safety, Environmental Impact, and Regulations

The increasing demand for sustainable alternatives to single-use plastics has driven significant research into edible straws. While their biodegradable nature makes them appealing, their safety, environmental impact, and regulatory compliance are paramount for successful market adoption. This chapter evaluates these aspects based on current developments and findings from recent studies.

## Safety Considerations in Edible Straws

Safety is a core requirement for any food-contact material, especially when it is intended to be edible. According to Han(2014), the base materials used in edible straws—such as starch, cellulose, gelatin, and seaweed—are generally recognized as safe (GRAS) by regulatory agencies like the U.S. Food and Drug Administration (FDA). However, the incorporation of additives, processing aids, and coatings must also comply with food safety standards.

While most research uses naturally derived, non- toxic ingredients, concerns remain over potential contamination and migration of unwanted chemicals. Timshina et al. (2021) highlighted the presence of per- and polyfluoro alkyl substances (PFAS) in some commercially available plant-based straws. Although these straws are marketed as eco- friendly, the leaching of PFAS poses a significant health hazard due to their persistence and bioaccumulation. This study underscores the necessity of comprehensive chemical characterization and screening before edible straws are commercialized.

Wei et al. (2023) examined starch-polyvinyl alcohol (PVA) composites and found that when PVA is used in small quantities, it enhances mechanical properties without compromising food safety. However, the purity and origin of such polymers need to be verified through toxicity studies. Similarly, Rai et al. (2023) demonstrated that bamboo-gelatin composite straws were safe and fully edible, provided that delignification and phosphorylation steps are carefully controlled to eliminate harmful residues.

## Environmental Sustainability and Lifecycle Impact

Environmental sustainability is one of the strongest

motivations behind edible straws. Unlike plastic straws that take hundreds of years to degrade, edible materials like starch, seaweed, and cellulose decompose quickly under composting or natural conditions. Ni et al. (2024) reported that seaweed- based straws showed excellent hydrostability during use but readily biodegraded post-disposal. These findings were supported by Kajla et al. (2024), who emphasized seaweed’s rapid compostability and low carbon footprint.

Liu et al. (2024) reviewed the biodegradability and life cycle assessments (LCA) of various bio-based straws. They concluded that starch-based straws not only decompose efficiently but can also be produced using low-energy processes such as extrusion. Similarly, He et al. (2023) and Cui et al. (2023) demonstrated that optimized retrogradation and cross linking of starch improved durability without introducing synthetic polymers, thus preserving the environmental value of the product.

Roy et al. (2021) took a broader perspective, analyzing the environmental, economic, and societal impacts of drinking straw evolution. Their study emphasized that while edible straws reduce plastic pollution, issues like resource consumption (e.g., agricultural inputs for starch or gelatin) and energy use during processing still require careful consideration. To truly outperform plastic straws, edible straws must be integrated into a circular economy model where waste is minimized, and materials are locally sourced.

## Regulations and Compliance

Edible straws must adhere to both food and environmental safety regulations, which vary across countries. Han (2014) and Gupta et al. (2024) emphasized the importance of aligning product formulation with existing food packaging laws. All materials and additives must be approved for human consumption, and their migration levels into beverages must stay below regulatory thresholds.

For cellulose- and protein-based straws, microbiological safety is a concern. Wu et al.(2024) indicated that edible films and coatings must be protected from microbial spoilage during storage, especially when proteins are involved. Proper drying, packaging, and possibly incorporation of natural antimicrobials are recommended to maintain shelf stability.

Furthermore, labeling and consumer education play an important role. Djekic et al. (2024) discussed quality perception among Generation Z and emphasized the importance of transparency regarding material composition and safety. This is particularly relevant given the influx of new materials and hybrid composites, such as beeswax- coated soy protein straws developed by Choeybundit et al. (2024).

Another key regulatory consideration is the need for standardized testing protocols. Liu et al. (2025) noted a lack of consistency in assessing mechanical, thermal, and biodegradability properties across different studies. Establishing universal testing standards will ensure that edible straws meet both industry expectations and legal compliance across international markets.

## Consumer Perception and Acceptance

Consumer safety perception also significantly impacts product success. Patil et al. (2025) and Yavagal et al. (2020) found that consumers are more likely to accept edible straws when safety, hygiene, and performance are clearly communicated. Sensory factors like taste, texture, and aroma must not interfere with the beverage experience, as emphasized by Han (2014). Additionally, Roy et al. (2021) stressed the importance of aligning product messaging with environmental ethics to reinforce consumer trust.

## CONSUMER ACCEPTANCE AND SENSORY CONSIDERATIONS

As edible straws transition from experimental innovation to commercial reality, their long-term viability depends heavily on consumer acceptance. Beyond safety and sustainability, sensory characteristics—such as texture, taste, appearance, and interaction with the beverage—are vital for user satisfaction. This chapter explores how sensory performance and consumer perception influence the acceptance of edible straws, drawing evidence from recent studies.

## TheRole of Sensory Properties in Consumer Experience

Sensory quality is a pivotal factor in determining the usability and marketability of edible straws. Han (2014) emphasized that edible films and coatings, when used in food-contact applications, must avoid altering the organoleptic properties of the products they accompany. The same principle applies to edible straws—materials must not leach undesirable flavors, odors, or textures into beverages. Cui et al. (2023) and Wei et al. (2023) demonstrated that starch-based straws could maintain structural integrity without negatively impacting taste if properly formulated. Their extrusion and retrogradation processes enhanced the mechanical strength of corn starch straws while keeping them inert in sensory terms. Similarly, Liu et al. (2024) pointed out that formulations involving glycerol and other plasticizers significantly influence not just mechanical flexibility but also surface texture and mouthfeel, which are critical for user acceptance.

## Texture and Mouthfeel

Texture and mouthfeel are among the most noticeable attributes during use. Consumers generally expect straws to be smooth, firm, and resistant to sogginess throughout the beverage consumption period. Patil et al.(2025)indicated that one of the main reasons consumers reject paper or plant-based straws is their tendency to degrade or become mushy. This limitation also applies to some edible straws, particularly those without coatings or reinforcement. Choeybundit et al.(2024)addressed this by developing composite straws using soy protein isolate and cassava starch, coated with beeswax and shellac wax. These coatings enhanced water resistance and maintained rigidity, offering a more traditional straw-like experience. Their study showed that combining sensory- appealing coatings with functional core materials improves consumer perception significantly.

## Taste and Odor Compatibility

Taste neutrality is essential, especially when edible straws are used with flavored or carbonated beverages. Rai et al. (2023) reported that straws made from bamboo-gelatin composites offered minimal sensory interference, making them acceptable across various drink types. However, the same cannot be said for all biopolymers. For example, seaweed-derived straws (Ni et al., 2024) sometimes retain slight marine notes unless carefully processed. Kajla et al. (2024) noted that purification and decolorization processes help remove such residual flavors, but these add to production complexity.Some researchers, Including Samiha et al.(2025),have explored enhancing sensory appeal by incorporating flavoring agents or herbal extracts. Their starch-based edible straws enriched with periwinkle extracts not only offered mild flavor enhancement but also added antioxidant functionality. However, flavored straws must be carefully matched with beverage profiles to avoid flavor clashes, a challenge highlighted by Han (2014) in her work on edible coatings.

## Visual Appeal and Customization

Visual aesthetics—color, clarity, and surface texture—play a significant role in consumer engagement. Yang et al. (2024) emphasized the growing popularity of smart packaging that incorporates natural colorants into cellulose hydrogels. Such innovations could be translated to edible straws, allowing vibrant, appealing designs without synthetic dyes. Djekic et al. (2024) found that Generation Z consumers particularly value eco- conscious products that still offer visual novelty and style. In their study of paper straws, participants associated colored and branded straws with higher quality and environmental value. Translating this insight to edible straws suggests opportunities in personalization and branding—features that can also enhance market competitiveness.

## Cultural and Behavioral Influences on Acceptance

Consumer acceptance is not solely dependent on product performance; it is also shaped by cultural norms, behavioral habits, and perceptions of sustainability. Roy et al.(2021)discussed the global transition from plastic to alternative straws, emphasizing how societal narratives about waste reduction and environmental stewardship affect buying decisions. Products that visibly align with these values—like edible straws—are more likely to succeed when they are framed as both functional and ethical choices. Moreover, Liu et al. (2024) noted that while many consumers express support for eco-friendly options, actual adoption rates depend on whether alternatives offer similar or better user experiences. This highlights the importance of matching or exceeding traditional straw performance to drive behavioral change.

## Perceived Hygiene and Storage

Although edible straws are safe and biodegradable, consumer concerns around hygiene remain a barrier. Han(2014) and Wu et al.(2024) pointed out

that edible materials can be susceptible to microbial contamination if not properly packaged or preserved. Individually wrapped straws, made from food-grade materials, may help alleviate these concerns, but they must not negate environmental benefits by introducing new forms of packaging waste.

## Identified Research Gaps

Despite growing academic and industrial interest in edible straws, several critical knowledge gaps and developmental challenges remain unaddressed. Bridging these gaps is essential for transitioning edible straws from prototype concepts to widely accepted, commercially viable alternatives to plastic straws. This chapter synthesizes the main areas where further research and innovation are required.

## Lack of Industrial-Scale Testing and Standardization

While laboratory-scale development has yielded promising outcomes, large-scale production of edible straws remains largely unexplored. Studies such as those by Cui et al. (2023) and He et al. (2023) rely on small-batch extrusion techniques with limited scalability. There is a pressing need for investigations that explore pilot-plant or industrial- scale operations, automation compatibility, and long-term shelf-stability under varied distribution conditions. Patil et al. (2025) observed that product performance can vary significantly with regional processing parameters, underlining the absence of global benchmarks for edible straw production. Similarly, Han (2014) stressed the importance of aligning edible straw production with food safety and packaging standards—like those enforced by the FDA or EFSA—especially in the context of moisture resistance, migration limits, and biodegradation rates. Standardized testing protocols and certification systems will be critical for industry-wide adoption.

## Limited Studies on Sensory Acceptability

Although edible straws are designed for direct food contact, sensory evaluation has been relatively overlooked in the literature. While mechanical, thermal, and barrier properties are widely studied, structured consumer testing for mouthfeel, taste, odor, and visual aesthetics remains limited. Liu et al. (2024) and Patil et al.(2025) acknowledged that undesirable flavors or soggy textures could deter consumers from repeat usage. Rai et al. (2023) provided appositive example, showing that bamboo- gelatin composites retained taste neutrality. Likewise, Choeybundit et al. (2024) addressed off- flavor issues by incorporating beeswax coatings. However, most starch and seaweed studies (e.g., Cui et al., 2023; Ni et al., 2024) fail to address how their formulations are perceived by consumers. Future research must prioritize multi-sensory evaluations across beverage types (hot, cold, carbonated, acidic). Sensory science methodologies—such as hedonic scaling, descriptive analysis, and temporal dominance of sensations—should be used to correlate formulation choices with user satisfaction.

## Cost-Performance Optimization

The balance between performance and cost remains a significant barrier to adoption. While cellulose and seaweed materials provide superior moisture resistance and durability, they incur higher production costs due to processing complexities (Yang et al., 2024; Kajla et al., 2024). Conversely, starch-based straws are cheaper but underperform in moist environments unless supplemented with synthetic plasticizers like PVA, which may raise biodegradability concerns (Wei et al.,2023). Roy et al. (2021) emphasized the need for a full cost-benefit lifecycle assessment, encompassing environmental impact, material input, energy consumption, and post-use decomposition. Current literature lacks comprehensive techno-economic analyses to help producers decide which biopolymer or blend is optimal for different markets and use-cases. Modeling frameworks should be developed that account for:

* + - Raw material availability and cost
		- Processing and energy expenditure
		- Packaging, transport, and shelf-life
		- Waste management and compost ability Such analyses would inform both industry

Investment and policy-making.

## Synergistic Blending of Materials

Single-component systems often struggle to meet all functional criteria, leading researchers to explore polymer blending. However, systematic studies exploring the synergistic potential of blends are still scarce. Combinations like starch–cellulose or protein–seaweed offer opportunities to balance flexibility, strength, and water resistance (He et al., 2023; Liu et al., 2024). Choeybundit et al. (2024) demonstrated the potential of soy protein–starch composites with wax coatings, while Chakravartula et al. (2019) used pectin–alginate–protein films to enhance mechanical and barrier properties. Yet few studies assess ternary or multi-phase systems that could harness the benefits of all three: strength, edibility, and barrier performance. Future directions include:

* + - Ternary blends: starch–cellulose–protein systems
		- Lipid-enhanced seaweed–protein composites
		- Nanofiber reinforcements with chitosan or nanocellulose

This approach can create tailored functionalities for different beverage types and market segments, reducing the need for synthetic additives.

## Innovation in Smart and Functional Straws

The edible straws pace remains largely functional in its current offerings, with limited innovation in smart or interactive features. Yang et al.(2024) introduced cellulose hydrogels with natural colorants that change hue with pH—an exciting development in smart packaging. Translating these features into straws could add value for consumers and industries alike. Emerging possibilities include:

* + - pH-sensitive straws that change color in acidic or spoiled drinks
		- Nutrient-fortified straws that release vitamins or antioxidants upon use
		- Branding-enabled smart materials, such as thermochromic or UV-reactive pigments for visual engagement
		- Bioluminescent coatings for novelty applications in food service

Such developments require interdisciplinary research involving materials science, food technology, and user experience design. Moreover, their commercialization will demand clarity on safety, biodegradability, and regulatory classification (e.g., whether additives count as functional foods or packaging).

# CONCLUSION

The evolution of edible straws represents a significant advancement in sustainable packaging technologies, aiming to mitigate the global environmental burden caused by single-use plastics. Through a comprehensive review of current materials, fabrication techniques, functional attributes, consumer perception, and industrial feasibility, this study highlights the multifaceted nature of edible straw development. Materials such as starch, cellulose, seaweed, and protein-based composites exhibit promising mechanical strength, biodegradability, and sensory neutrality, especially when tailored with suitable additives or modified through advanced processing techniques like extrusion, cross linking, and surface coatings (Cuietal.,2023; Heetal.,2023;Choeybundit et al., 2024; Qin et al., 2022).

Despite substantial progress, significant gaps persist. Industrial-scale testing remains under explored, and the lack of standardized evaluation frameworks hampers large-scale commercialization. Additionally, sensory evaluation—an essential determinant of consumer acceptance—is underrepresented in the literature, necessitating future research that integrates functional performance with organoleptic quality(Liu et al.,2024; Patil et al., 2025). Moreover, there is a pressing need for cost-performance optimization models to balance environmental sustainability with economic viability, particularly for emerging biopolymers like nanocellulose and functionalized seaweed derivatives (Yang et al., 2024; Kajla et al., 2024).

To further push the boundaries of edible packaging, interdisciplinary efforts should focus on the development of synergistic material blends—such as starch–cellulose–protein composites—and the incorporation of smart functionalities like pH- responsive or nutritionally active straws(Ni et al.,2024; Samiha et al., 2025). Such innovations could bridge functionality with novelty, making edible straws both a sustainable and value-added product in the modern foodservice landscape.

In conclusion, edible straws embody the convergence of material science, environmental responsibility, and consumer-centric design. With the right blend of scientific rigor, regulatory alignment, and market adaptation, they hold great potential as eco-conscious alternatives capable of transforming food packaging ecosystems worldwide.

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