A Review on Edible Straws

# ABSTRACT

Plastic pollution remains one of the most pressing environmental challenges of the 21st century, with single-use plastic straws contributing significantly to marine litter and microplastic accumulation. In response, edible straws have emerged as a promising biodegradable alternative aligned with global efforts to reduce plastic consumption. This review synthesizes insights from 32 Scopus-indexed studies (2020–2025), highlighting advancements in raw materials, processing methods, mechanical strength, environmental sustainability, and consumer perception. Edible straws are primarily manufactured using renewable, food-grade biopolymers such as starch (from cassava, corn, rice), seaweed polysaccharides (agar, alginate, carrageenan), cellulose (agro-waste derived), and proteins (soy, whey, gelatin), with functional additives like plasticizers (glycerol, sorbitol) and hydrophobic coatings (beeswax, shellac) enhancing their performance. Among them, cellulose-based straws show high tensile strength and moisture resistance, while protein- and seaweed-based versions offer favorable sensory profiles and faster biodegradation. Despite these benefits, challenges such as high production costs, short shelf life, variability in material behavior, and lack of regulatory standardization limit market penetration. Life cycle assessments confirm the ecological advantages of edible straws over plastic and paper alternatives. Innovative developments such as hybrid biopolymer blends, nanofillers, scalable extrusion techniques, and flavor-infused designs hold promise for enhancing commercial viability and user acceptance. Achieving mainstream adoption will require integrated efforts in material science, food engineering, policy regulation, and public awareness.

**Keywords:** *Edible packaging, Edible straws, Biodegradable utensils, Seaweed bioplastics, Starch-based films, Sustainable packaging, Consumer acceptance, Food-grade materials*

### INTRODUCTION

The increasing environmental concerns arising from the excessive use of synthetic, petroleum- based plastics have sparked global efforts to find sustainable, biodegradable, and eco-friendly alternatives in food packaging. Among various categories of biopolymers and green innovations, edible packaging has gained considerable attention due to its unique ability to be safely consumed along with the food product it protects, 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).

Edible packaging is emerging as a sustainable alternative to conventional plastics due to its biodegradability and edibility. Derived from natural polymers like proteins, polysaccharides, and lipids, these materials extend shelf life while minimizing environmental impact (Kour, Aradhna, & Rajput, 2025). Recent innovations integrate antimicrobial agents and smart indicators, with nanotechnology increasing mechanical and functional performance (Tomar, Sinhamahapatra, & Sharma, 2025).

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 slow degradation time— estimated at 300 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 structural durability (Djekic *et al.,* 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, and consumer acceptability (Patil *et al.,* 2025; Kajla *et al.,* 2024).

Edible packaging materials rely heavily on natural polymers, primarily polysaccharides and proteins, 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 method has significantly improved the mechanical 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 bonding interactions, resulting in improved tensile 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, super hydrophobicity, 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 innovations utilize bacterial cellulose modified with soy protein and calcium alginate to produce low- hygroscopic, edible films with oil resistance and excellent optical clarity (Cheung *et al.,* 2023). The valorization of agro-waste, such as rice straw, 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 high water stability and structural resilience, which can even incorporate natural pigments for freshness indication in beverages (Ni *et al.,* 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 waxes such as beeswax and shellac has

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 packaging relies not only on technical performance but 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 evaluation criteria to assess the compatibility of edible 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 the very purpose of offering a clean, green alternative (Timshina et al., 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 optimized to maintain balance between water

permeability, strength, and biodegradation (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 edible packaging systems that serve as genuine replacements for traditional plastics.

# MATERIALS FOR EDIBLE STRAW FABRICATION

* 1. **Starch**

Starch is one of the most widely used biopolymers in edible straw production due to its availability, biodegradability, and excellent film- forming ability. It is derived from various botanical sources such as corn, 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, which often necessitate modification or blending 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 straws with strong mechanical properties through optimized extrusion and retrogradation, resulting in improved strength and reduced solubility. In a complementary study, He *et al*. (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.

Plasticizers such as glycerol and polyvinyl alcohol

(PVA) are also frequently incorporated to improve flexibility and toughness. Liu *et al.* (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 Putri and 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 superhydrophobic 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, hydro stable 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 freshwater, 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 beeswax 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.

Table 1: comparison of edible straw materials

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Material Type** | **Sources** | **Key Properties** | **Strengths** | **Limitations** |
| **Starch** | Corn, rice, cassava starch (Cui *et al.,* 2023; He et al., 2023;  Putri & Falah, 2022) | Biodegradable, good film-forming, water sensitive, improved by  retrogradation 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; Cheung *et al*., 2023; Islam *et al.,* 2023) | Strong, hydrophobic when modified, low hygroscopicity, renewable | Excellent strength, structure retention, environmentally friendly (Yang *et al.,* 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 (Ni *et al.,* 2024) |
| **Proteins & Composites** | Gelatin, soy protein isolate, whey protein (Rai et al., 2023; Choeybundit et al., 2024; Chakravartula *et*  *al*., 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.

### Crosslinking and Reinforcement

Crosslinking 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. Crosslinking 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 beeswax 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 *et al.* (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 crosslinking, 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 24 hours 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, crosslinking, 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 crosslinking 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 crosslinking.

Qin *et al.* (2022) used plasma treatment on cellulose to create a superhydrophobic 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 other hand, 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 hydrogels 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.

Table 2: 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 crosslinking | 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 crosslinking. 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 polyfluoroalkyl 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 crosslinking 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.

### The Role 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 a positive 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 compostability 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 straw space 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 foodservice

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, crosslinking, and surface coatings (Cui *et al.,* 2023; He *et al.,* 2023; Choeybundit *et al.,* 2024; Qin *et al.,* 2022).

Despite substantial progress, significant gaps persist. Industrial-scale testing remains underexplored, 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

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Functionalized seaweed derivatives (Yang *et al.,* 2024; **References**

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.

1. Agumba, D. O., Pham, D. H., & Kim, J. (2023). Ultrastrong, hydrostable, and degradable straws derived from microplastic- free thermoset films for sustainable development. *ACS Omega, 8*(8), 7448–7456. <https://doi.org/10.1021/acsomega.2c07797>
2. Baneshi, M., Aryee, A. N. A., English, M., & Mkandawire, M. (2024). Designing plant- based smart food packaging solutions for prolonging consumable life of perishable foods. *Food Chemistry Advances, 5*, 100769. <https://doi.org/10.1016/j.focha.2024.100769>
3. Birania, S., Kumar, S., Kumar, N., Attkan, A. K., Panghal, A., Rohilla, P., & Kumar, R. (2021). Advances in development of biodegradable food packaging material from agricultural and agro-industry waste. *Journal of Food Process Engineering, 45*(2), e13930. <https://doi.org/10.1111/jfpe.13930>

## Chakravartula, S. S. N., Soccio, M., Lotti, N., Balestra, F., Dalla Rosa, M., & Siracusa, V.

(2019). Characterization of composite edible films based on pectin/alginate/whey protein concentrate. *Materials, 12*(15), 2454. <https://doi.org/10.3390/ma12152454>

1. Cheung, K. M., Jiang, Z., & Ngai, T. (2023). Edible, strong, and low-hygroscopic bacterial cellulose derived from biosynthesis and physical modification for food packaging. *Journal of the Science of Food and Agriculture, 103*(14), 7129–7137. <https://doi.org/10.1002/jsfa.12758>
2. Choeybundit, W., Karbowiak, T., Lagorce, A., Ngiwngam, K., Auras, R., Rachtanapun, P., Noiwan, D., & Tongdeesoontorn, W. (2024). Eco-friendly straws: A fusion of soy protein isolate and cassava starch coated with beeswax and shellac wax. *Polymers, 16*(13), 1887. <https://doi.org/10.3390/polym16131887>
3. Cui, C., Zhao, S., Zhang, Z., Li, M., Shi, R., & Sun, Q. (2023). Preparation and characterization of corn starch straws with strong mechanical properties by extrusion and retrogradation. *Industrial Crops and Products, 191*(Part A), 115991. <https://doi.org/10.1016/j.indcrop.2022.115991>

## Djekic, I., Petrovic, T., Smigic, N., Udovicki, B., & Tomic, N. (2024). Confronting various quality perspectives of paper straws—Case study with Generation Z. *Applied Sciences, 14*(23), 11189.

<https://doi.org/10.3390/app142311189>

1. Duizer, L. M., Robertson, T., & Han, J. (2008). Requirements for packaging from an ageing consumer's perspective. *Packaging Technology and Science, 21*(8), 521–532. <https://doi.org/10.1002/pts.834>

## Gupta, D. K., Phanisree, M. H. M., Penchalaraju, M., & Babu, A. S. (2024). Edible and biodegradable polymeric materials for food packaging or coatings. In

M. Sen (Ed.), *Food Coatings and Preservation Technologies* (Chapter 3). Wiley. [https://doi.org/10.1002/9781394237623.ch](https://doi.org/10.1002/9781394237623.ch3) [3](https://doi.org/10.1002/9781394237623.ch3)

1. Han, J. H. (2014). Edible films and coatings: A review. In J. H. Han (Ed.), *Innovations in Food Packaging* (2nd ed., pp. 213–255). Academic Press. [https://doi.org/10.1016/B978-0-12-394601-](https://doi.org/10.1016/B978-0-12-394601-0.00009-6) [0.00009-6](https://doi.org/10.1016/B978-0-12-394601-0.00009-6)

## He, X., Zhao, S., Zhang, Z., Dai, L., Qin, Y., Ji,

N., Xiong, L., Shi, R., & Sun, Q. (2023). A

combined extrusion, retrogradation, and cross-linking strategy for preparing starch- based straws with desirable mechanical properties. *International Journal of Biological Macromolecules, 227*, 1089–1097. <https://doi.org/10.1016/j.ijbiomac.2022.11.289>

## Hu, W., Xu, X., Wang, X., Ma, T., Li, Y., Qin,

X., Wei, J., & Chen, S. (2024). Effect of curdlan on the gel properties and interactions of whey protein isolate gels. *International Journal of Biological Macromolecules, 277*(Part 3), 134161.

<https://doi.org/10.1016/j.ijbiomac.2024.134161>

1. Islam, M., Saini, P., Das, R., Shekhar, S., Sinha, A. S. K., & Prasad, K. (2023). Rice straw as a source of nanocellulose for sustainable food packaging materials: A review. *BioResources, 18*(1), 1–22. <https://doi.org/10.15376/biores.18.1.Islam>

## Kajla, P., Chaudhary, V., Dewan, A., Bangar,

S. P., Ramniwas, S., Rustagi, S., & Pandiselvam, R. (2024). Seaweed-based biopolymers for food packaging: A sustainable approach for a cleaner tomorrow. *International Journal of Biological Macromolecules, 274*(Part 1), 133166.

<https://doi.org/10.1016/j.ijbiomac.2024.133166>

## Kim, J.-S., Ahn, J., Lee, S.-J., Moon, B., Ha,

T.-Y., & Kim, S. (2011). Phytochemicals and antioxidant activity of fruits and leaves of paprika (Capsicum annuum L., var. Special) cultivated in Korea. *Journal of Food Science, 76*(1), C193–C198.

[https://doi.org/10.1111/j.1750-](https://doi.org/10.1111/j.1750-3841.2010.01891.x) [3841.2010.01891.x](https://doi.org/10.1111/j.1750-3841.2010.01891.x)

1. Kour, M., Aradhna, & Rajput, R. (2025). A comprehensive review on edible packaging on sustainable food system. *European Journal of Nutrition & Food Safety, 17*(5), 153–164. <https://doi.org/10.9734/ejnfs/2025/v17i51715>
2. Kumar, A. V., Hasan, M., Mangaraj, S., Pravitha, M., Verma, D. K., & Srivastav, P. P. (2022). Trends in edible packaging films and its prospective future in food: A review. *Applied Food Research, 2*(1), 100118. <https://doi.org/10.1016/j.afres.2022.100118>
3. Liu, P., Li, Y., Wang, D., Xu, R., Jiang, Y.,

Qiao, X., Gao, W., Yu, B., & Cui, B. (2025).

Effects of different ratios of water and glycerol on the physicochemical properties of starch-based straws. *Food Chemistry, 466*, 142215.

[https://doi.org/10.1016/j.foodchem.2024.1422](https://doi.org/10.1016/j.foodchem.2024.142215) [15](https://doi.org/10.1016/j.foodchem.2024.142215)

## Liu, Y., Li, N., Zhang, X., Wei, T., Ma, M.,

Sun, Q., Li, M., & Xie, F. (2024). Eco-friendly drinking straws: Navigating challenges and innovations. *Trends in Food Science & Technology, 148*, 104511. <https://doi.org/10.1016/j.tifs.2024.104511>

## Ni, H., Li, H., Hou, W., Chen, J., Miao, S.,

Wang, Y., & Li, H. (2024). From sea to sea: Edible, hydrostable, and degradable straws based on seaweed-derived insoluble cellulose fibers and soluble polysaccharides. *Carbohydrate Polymers, 334*, 122038. <https://doi.org/10.1016/j.carbpol.2024.122038>

## Patil, T. D., Bisht, S., Meshram, B. P., & Gaikwad, K. K. (2025). A review on emerging trends and developments in edible drinking straws for food and beverage applications. *Trends in Food Science & Technology, 163*, 105158.

<https://doi.org/10.1016/j.tifs.2025.105158>

## Putri, H. V., & Falah, M. A. F. (2022).

Development of biodegradable straw using combination of unused rice and rice bran. *Agroindustrial Journal, 8*(2), 550–559. <https://doi.org/10.22146/aij.v8i2.76725>

1. Qin, L., Liu, Z., Liu, T., Liu, S., Zhang, J., Wu, J., & Liang, X. (2022). A bioinspired, strong, all-natural, superhydrophobic cellulose-based straw. *International Journal of Biological Macromolecules, 220*, 910–919. <https://doi.org/10.1016/j.ijbiomac.2022.08.118>

## Rai, R., Ranjan, R., Kant, C., & Dhar, P. (2023). Biodegradable, eco-friendly, and hydrophobic drinking straws based on delignified phosphorylated bamboo-gelatin composites. *Chemical Engineering Journal, 471*, 144047.

<https://doi.org/10.1016/j.cej.2023.144047>

## Roy, P., Ashton, L., Wang, T., Corradini, M. G., Fraser, E. D. G., Thimmanagari, M.,

Tiessan, M., Bali, A., Saharan, K. M., Mohanty, A. K., & Misra, M. (2021). Evolution of drinking straws and their environmental,

economic and societal implications. *Journal of Cleaner Production, 316*, 128234. <https://doi.org/10.1016/j.jclepro.2021.128234>

1. Samiha, S., Karan, I., & Renuka, V. (2025). Development of biodegradable starch-based edible films enhanced with periwinkle extracts for sustainable food packaging. *International Research Journal on Advanced Engineering Hub (IRJAEH), 3*(4), 1797–1803.

<https://doi.org/10.47392/IRJAEH.2025.0260>

1. Sanyang, M. L., Sapuan, S. M., Jawaid, M., Ishak, M. R., & Sahari, J. (2016). Effect of plasticizer type and concentration on physical properties of biodegradable films based on sugar palm (Arenga pinnata) starch for food packaging. *Journal of Food Science and Technology, 53*(1), 326–336. <https://doi.org/10.1007/s13197-015-2009-7>
2. Timshina, A., Aristizabal-Henao, J. J., Da Silva, B. F., & Bowden, J. A. (2021). The last straw: Characterization of per- and polyfluoroalkyl substances in commercially- available plant-based drinking straws. *Chemosphere, 277*, 130238. [https://doi.org/10.1016/j.chemosphere.2021.1](https://doi.org/10.1016/j.chemosphere.2021.130238) [30238](https://doi.org/10.1016/j.chemosphere.2021.130238)

## Tomar, R., Sinhamahapatra, M., & Sharma, P.

K. (2025). Recent progress and emerging trends of antimicrobial edible food packaging. *Journal of Advances in Biology & Biotechnology, 28*(3), 873–893. <https://doi.org/10.9734/jabb/2025/v28i32145>

## Wei, X., Tao, H., Tan, C., Xie, J., Yuan, F.,

Guo, L., Cui, B., Zou, F., Gao, W., Liu, P., & Lu, L. (2023). Intermolecular interactions between starch and polyvinyl alcohol for improving mechanical properties of starch- based straws. *International Journal of Biological Macromolecules, 239*, 124211. <https://doi.org/10.1016/j.ijbiomac.2023.124211>

## Wu, Y., Wu, H., & Hu, L. (2024). Recent

advances of proteins, polysaccharides and lipids-based edible films/coatings for food packaging applications: A review. *Food Biophysics, 19*(1), 29–45. <https://doi.org/10.1007/s11483-023-09794-7>

## Yavagal, P. S., Kulkarni, P. A., Patil, N. M.,

Salimath, N. S., Patil, A. Y., Savadi, R. S., & Kotturshettar, B. B. (2020). Cleaner production of edible straw as replacement for thermoset plastic. *Materials Today:*

*Proceedings, 32*(Part 3), 492–497. <https://doi.org/10.1016/j.matpr.2020.02.667>

1. Yang, L., Yuan, Q.-Y., Lou, C.-W., Lin, J.-H.,

& Li, T.-T. (2024). Recent advances of cellulose-based hydrogels combined with

natural colorants in smart food packaging.

*Gels, 10*(12), 755.

<https://doi.org/10.3390/gels10120755>