

Mucilage based Bioplastic: Review on Sustainable Production and Application

Puli Madhuri¹, N Nirmala², J Merlin²

¹*Department of Biotechnology, Sathyabama Institute of science and technology, Tamil Nadu, Chennai -600119, India*

^{2,3}*International Research Centre, Sathyabama Institute of science and technology, Tamil Nadu, Chennai -600119, India*

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Abstract- Petroleum-based bioplastic has become escalating environmental burden and has prompted an urgent global pursuit which include sustainable, biodegradable alternatives derived from renewable sources. Both production and decaying of plastics release toxic chemicals contributing to global warming, ozone layer depletion. Polymers derived from plants have been an ultimate solution to this problem because of their promising future with biodegradability, cost-effectiveness and compatibility with circular economy principles. Even though, plant-based biopolymers are good, among them, cactus mucilage (*Opuntia Ficus Indica*) gained attention for its properties such as heteropolysaccharide composition, water-binding capacity, and its ability to form biofilms and these biofilms can be used for Packing purposes. However, Mucilage structural composition varies from plant to plant and their extraction methods that has been reported by researchers impact the potential of cactus mucilage. Some reinforcement challenges like glycerol plasticizers, inorganic fillers and cross-linking agents like urea is employed, which resulted in visible improvements in flexibility, strength and biodegradability. These enhancements help in increasing the use of cactus mucilage-based films in packaging and agricultural applications.

Key words: biodegradable, biopolymers, mucilage, properties, sustainable

I. INTRODUCTION

Plastics have become a part of life and widely used material in modern society. Considering their durability, versatility, and low production cost, plastic has been seen in many applications mostly in construction, packaging, textiles, automotive, and healthcare. The other side of the coin is different, the nature of these petroleum-based plastics is non-biodegradability and they persist in ecosystems for decades in turn possessing significant environmental concerns and threat to living beings.

Over their entire life, plastics generate greenhouse gas emissions, starting with their production, which primarily depends on energy-intensive procedures including the processing of fossil fuels, and ending with their disposal, which requires energy and generates emissions immediately [39]. Plastic consumption has thus increased about 180 times from 1950 to 2018. The worldwide plastic production is calculated to be 400.3 million tons in 2022[30]. Around 40 % of global plastic production is used for packaging, making packaging the largest plastic production market [14], most of plastics used for packaging are mechanically recyclable; however, only 14 % of plastic packaging is collected for recycling. They are mostly recycled into lower-value applications, and cannot be recycled again beneficially from an economic point of view.

The accumulation of plastic waste contributes to greenhouse gas emissions, soil and water pollution, and poses hazards to human and ecological health. Disturbances in ecosystem is mainly caused by the plastic pollution and 70 % of plastic waste is being dumped in aquatic ecosystem. The negative impact of marine plastic pollution clearly goes beyond countries' borders in a spillover effect that needs to be traced [40] As such, the synthesis of biodegradable plastics from agricultural wastes/biomasses has gained attention year by year due to their cost effectiveness, availability, biodegradability and environmentally benign properties [2]. Biobased and biodegradable plastics can contribute to a more sustainable society through the use of renewable resources and contribute to the reduction in CO₂ emissions during production [46]. Environmental trade-offs related to water, land, and energy usage in in biopolymer production has been a persisting challenge.

Among the alternative strategies, one of the best solution and promising candidates for this emerging problem is plant-derived biopolymers. Bioplastics are polymers that are manufactured into the commercial products from natural sources or renewable resources, and they can also be biodegradable [3]. These polymers replace the conventional plastics, and owe for their biodegradable, renewable and functional versatility properties. Although all the plants are good for biopolymer production, spotlight was given to cactus mucilage, mostly extracted from *O.ficus-indica* due to its low cost and environmentally friendly material. Mucilage is a heteropolysaccharide with high water-binding capacity and rheological flexibility, making it good application in food processing, pharmaceutical formulations, and biodegradable film development. Although it has more advantages, limitations for mucilage-based films are their poor mechanical stability and thermal stability, to mitigate methods like plasticization, cross-linking, or blending with other biopolymers are used.

Many recent researches exploring its structural characterization, extraction methods, and biofilm applications. Bibliometric analyses confirm a significant rise in global research output, particularly in Tunisia, the United States, Germany, Luxembourg, and Brazil, focusing on mucilage's functionalization and integration with complementary biopolymers such as starch, chitosan, and gelatin [34]. These studies illustrate the growing scientific consensus around cactus mucilage and make it best alternative to petroleum-based plastic with its highlighting properties such as moisture barrier properties, biodegradability, and potential for active packaging solutions.

Cactus mucilage, predominantly sourced from *O.ficus-indica* (prickly pear), is a polysaccharide-rich hydrocolloid with diverse applications in food, pharmaceuticals, and environmental sectors. Reviewing the potential of cactus mucilage within wide range of plant-based bioplastics is necessary to recognize current knowledge gaps, advancements, and future opportunities. This paper therefore aims to synthesize insights from recent experimental, structural, bibliometric, and sustainability studies to present a comprehensive perspective on the role of cactus mucilage and plant-derived polymers in the transition toward green and circular economies. Different types of extraction methods and plant

agro-climatic conditions impact the physiochemical profile, directly affecting gelling ability, viscosity, and performance of biofilm. With such variation in structural and compositional diversity, standardization efforts and harmonized extraction methods are used to make sure reproducibility in industrial-scale applications.

Other than cactus-derived polymers, there is inclusive shift towards plant-based bioplastics which include cellulose, starch, soy protein, and bamboo fiber composites gives possible reasons to slowly replace petroleum-derived plastics. The combination of mucilage with other biopolymers such as starch, gelatin, chitosan, and plasticizers, appears with purpose of optimizing the hydrophilic-hydrophobic and mechanical characteristics of polymeric films. Not only cactus mucilage, other plants mucilage and seeds such as chia and flax seeds has been promising towards the production of plant-based biopolymers [34].

This paper reviews the structural, chemical, and physical properties of mucilage, along with its extraction methods and applications explored in the research, where mucilage-based films serve as non-toxic, biodegradable, and functional alternative to synthetic plastics. Finally, it also designates some challenges such as sensitivity to moisture, scalability, and cost, while addressing future perspectives like nanocomposite reinforcement industrial standardization to scaling up the production. In the end, cactus mucilage comes across as a flexible, eco-friendly material that could help to cut down on plastic waste and helps in sustainable environment.

II. DIFFERENT SOURCES OF MUCILAGE

Mucilage is a complex water-soluble polysaccharide which is mainly composed of monosaccharides and uronic acids linked with glycosidic bonds, glycoproteins and bioactive [3]

2.1 Seeds

2.1.1 Basil seeds

Basil seeds — commonly obtained from *Ocimum basilicum L.*, a member of the mint family — are more than just smoothie add-ins. These small, black seeds have been traditionally grown across Asia, Africa, and the Americas, and are particularly significant in Iranian herbal medicine, where basil is considered an indigenous and highly valued

products. In fact, basil seeds can contain 17–20% mucilage by weight, and this mucilage is highly hydrophilic, meaning it absorbs water very efficiently. That property makes it incredibly useful in food and pharmaceutical products where gelling, thickening, or moisture-retaining properties are needed. The primary component of basil seed mucilage is glucomannan, a polysaccharide known for its high water-holding capacity and acid stability (43%). It has a glucose-to-mannose ratio of 10:2, making it particularly functional in acidic environments like the human stomach or certain food product.

2.1.2 Flax seeds

Flax seeds which are widely used as edible food for its nutritional value also has impressive mucilage – gel like sticky substance that is found in the seed coat. This mucilage consists of rhamnogalacturonan I and arabinoxylan, with novel side group substitutions that form large aggregates in solution and contribute to its gel-like character [29]. From the tensile test, it was concluded that the film's flexibility and extensibility was notably enhanced with the addition of glycerol as a plasticizer, adequate even at 1 wt% [41]. This mucilage is packed with beneficial compounds such as dietary fiber, proteins, fats, flavonoids, lignans, and phenolic compounds. From a composition standpoint, flaxseed mucilage is made up of about 83.3% polysaccharides, 4.6% proteins, and 11.8% ash. Most of the polysaccharides — roughly 75% — are neutral sugars, primarily in the form of arabinoxylans, which contribute to the mucilage's viscosity and gel-forming ability. The remaining 25% are acidic polysaccharides, particularly rhamnogalacturonans, which play roles in cell interaction and hydration [32]. The gel-forming ability of the mucilage adds strength to the film formation and tensile strength. Presence of polyunsaturated fatty acids in flaxseeds mucilage contribute to the mucilage's antibacterial, antioxidant, and even anti-inflammatory properties, makes it best for the packaging films and also making it a promising candidate for therapeutic and cosmetic formulations. Interestingly, studies have shown that certain polypeptide precursors found in flax mucilage can stimulate collagen production, aiding in wound healing. This gives it potential for use in surgical dressings and other medical materials.

2.1.3 Chia seeds

Chia seeds are packed with nutrients, typically made up of 37–45% carbohydrates, 31–34% healthy fats, 23–35% dietary fiber, and 16–26% protein, making them a well-rounded and nutritious food. Chia seeds are good source of dietary fiber, protein, antioxidants and poly unsaturated fats such as linoleic and lenolenic acids [37]. This nutrient-dense profile makes chia seeds a popular choice for health-conscious diets and functional foods. Mucilage extracted from chia seed is a promising natural material for the food industry due to its emulsifying and stability properties [4]. One of the standout features of chia seeds is their ability to absorb water and swell into a gel-like coating when hydrated. This forms what's known as chia seed mucilage (CSM) — a fiber-rich, transparent gel that's full of polysaccharides. This mucilage isn't just a curious kitchen phenomenon; it's highly functional and valuable in food science. Chia seed mucilage has been studied for a wide range of applications. It can step in for fat, improve texture, and help keep foods smooth, creamy, and well-mixed. These properties are largely due to its viscosity, gel-forming ability, and emulsion stability, making it an excellent clean-label alternative to synthetic thickeners or emulsifiers in both food and cosmetic products.

Extraction of seed mucilage

Selected seed mucilage was extracted by soaking seeds in water at a 1:10 . Before extraction, seeds were initially washed with water in autoclaved beakers. First, the seeds were soaked in water for 3 hours in an incubator set to 60 °C. After that, they were left to soak at room temperature overnight for about 12 to 14 hours. Once the seeds had fully swollen, the ones that could easily drain through a mesh were collected and placed into bags, ready for freeze-drying (lyophilization). Seeds such as those Basil and chia seeds were simply placed in bags as they were. After freeze-drying, their mucilage was separated by gently rubbing the dried seeds over a mesh and for its quality store the mucilage at –80 °C.

2.2 Cactus

The composition of mucilage includes carbohydrates, ash and moisture, which together make up approximately 93 % of the extract's weight. Proteins, crude fiber and a small amount of fat make rest of the composition. The carbohydrate part is made up of a complex mix of sugars—known as a heteropolysaccharide—that includes sugar residues like arabinose, rhamnose, xylose, and galactose,

plus varying amounts of galacturonic acid. Interestingly, how the plant is grown changes everything, when it comes to its quality and performance, factors like irrigation levels can have a big impact on the yield, composition, and physical properties of the mucilage.

When plants don't get much water, they usually produce mucilage with less ash, but more protein, fiber, carbohydrates, arabinose, glucose, and uronic acids. This mucilage tend to be thicker and have gel-like structure because of their high viscosity and large molecular size. It's actually kind of fascinating—plants under water stress seem to make better-quality mucilage, which really shows how much growing conditions matter and can influence the final product. Mucilage from *O. ficus-indica* is an interesting ingredient for the food industry because of its viscosity [38].

One of the great things about cactus mucilage is that it doesn't get thrown off by changes in pH, temperature, or salt levels — unlike some other stabilizers like proteins or synthetic surfactants. Because of this, it's becoming more and more popular, not just in food products, but also in things like cosmetics and medicine. Researchers are also looking into its use for things like microencapsulation (which helps deliver ingredients more effectively), eco-friendly plastics, and even cleaning up water. the glucose anomers contribute to about (64.13%) of the total chemical composition of the sample. Unlike pectin, OPI mucilage exhibited characteristic peaks of the two α - and β -isomers of arabinose (15.50%), xylose (6.43%), and galactose (8.34%).

The main components of mucilage are sugars, which make up more than 55% of its weight, and ash, primarily consisting of essential minerals like calcium and potassium [11]. During the extraction process, some minor components such as proteins and phenolic compounds may be partially lost. However, these components play important functional roles: proteins contribute to the mucilage's emulsifying ability, while phenolic compounds provide antioxidant properties.

Research has found that mucilage contains both polar and nonpolar amino acids, but glutamine and aspartic acid are present in the highest amounts. These amino acids not only enhance the nutritional profile of the mucilage but may also influence its functional behaviour in formulations. The balance of

these components makes cactus mucilage a multifunctional ingredient with potential in food, pharmaceutical, and cosmetic applications. The cactus cladodes are a source of mucilage that can be used as an edible coating on foods.

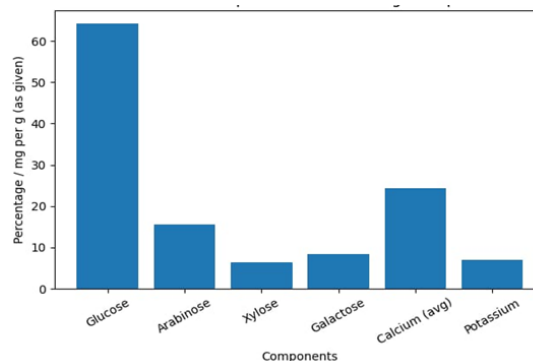


Fig 1: Chemical composition of Cactus Mucilage

Benefits of Cactus Mucilage

Cactus mucilage is a valuable natural polymer that offers broad range of benefits, making it best choice for bioplastic applications and other industries. Because of Its biodegradability products made from it reduce environmental pollution compared to conventional plastics. Its hydrophilic nature of mucilage, this substance can efficiently retain water, which is advantageous in food packaging, wound dressings, and agricultural coatings. Additionally, the benefit that it can provide is that it can act as natural barrier against oxygen and moisture, property that extend the shelf life and also helps in preserving perishable foods. Cactus mucilage also possesses antioxidant properties, which can protect sensitive food components from oxidation and spoilage. Moreover, it is non-toxic, edible, and safe for human and animal consumption, which makes it suitable for edible films and coatings. To dial up the things like thermal stability, mechanical strength, depending on what they need, Scientists can also modify its chemical makeup. Overall, cactus mucilage combines environmental sustainability with functional advantages, which is why it has gained considerable attention in recent studies focused on natural polymers and biodegradable materials [15].

Structure of Cactus Mucilage

Cactus mucilage, a complex polysaccharide-rich substance, primarily sourced from *Opuntia* species. [7] The arabinose, galactose, rhamnose, and xylose which are known as neutral sugars, along with

uronic acids like galacturonic acid are predominantly included in its molecular composition. This unique structure imparts distinct rheological properties to the mucilage, making it an excellent candidate for various applications, including biodegradable films and coatings [26].

The properties such as flexibility and strength which are essential for packaging materials is enabled by the molecular arrangement of the mucilage. The crucial thing for optimizing its use in sustainable material development is understanding the intricate cactus mucilage structure.

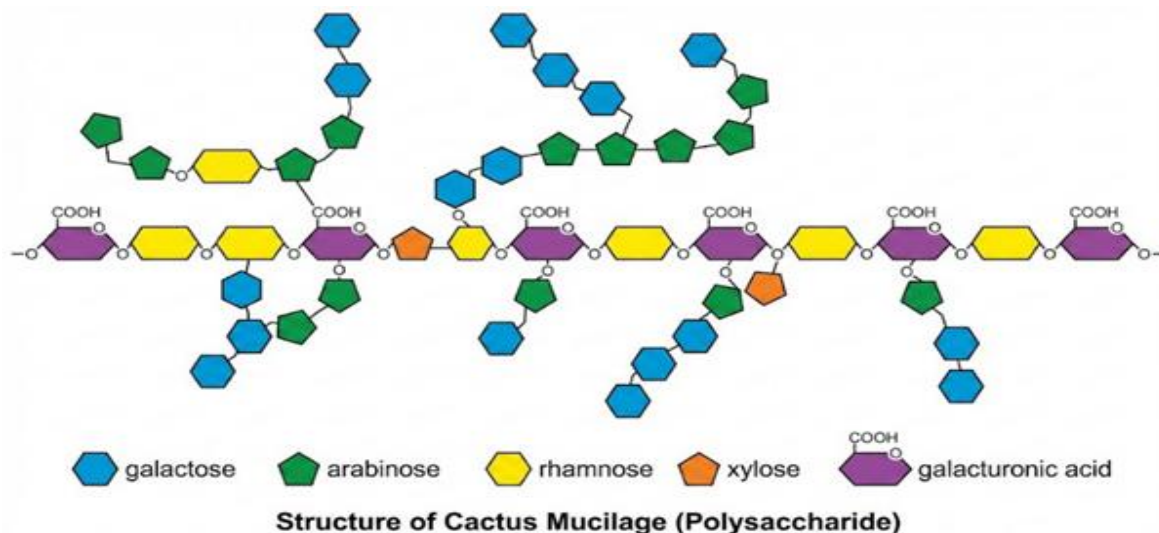


Fig 2 : Structure of Cactus Mucilage (Polysaccharide)

Physical Properties

The physical properties of cactus mucilage significantly influence its performance as a bioplastic [26]. The quality and ease of processing of the final product is affected by its viscosity and this can be adjusted by varying concentration and extraction methods. Another critical factor that determines the moisture barrier properties of the film is water retention capacity of the cactus mucilage. To increase the mechanical strength of cactus mucilage, plasticizers can be added so that the mechanical strength of cactus mucilage films can be enhanced, making them more suitable for various applications. These properties make cactus mucilage a promising candidate for biodegradable materials.

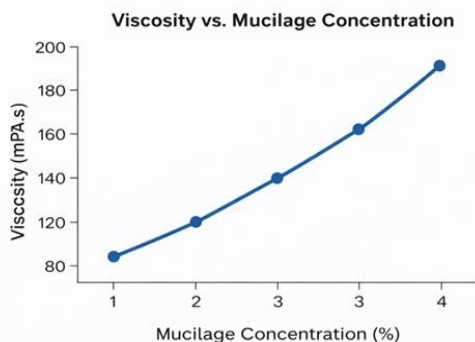


Fig 3: Viscosity depends on mucilage concentration
Chemical Properties

The chemical properties of cactus mucilage are integral to its functionality as a bioplastic. The sugars found in mucilage are arabinose (35–40%), galactose (20–25%), rhamnose (7–8%), xylose (20–25%) and uronic acids (7–8%) [25]. As shown in the fig 2.1, these sugars form a long chain like polysaccharide which includes galacturonic acid too. Arabinose and xylose sugars are branches on the galactoseside chains [36]. The hydroxyl and carboxyl groups, specific functional groups, contributes to its film-forming ability and interactions with other materials. Thermal stability plays a big role in how durable cactus mucilage films are, and their sensitivity to pH affects how well they perform in different environments. These chemical characteristics are crucial for tailoring the material to specific applications. In general, the stems of cactus contain varying proportions of D-galactose, L-arabinose (pyranose and furanose forms), D-xylose, and L-rhamnose and as the major neutral sugar units as well as D-galacturonic acid [12].

Composition

Not all cactus mucilage is created equal. It shifts depending on the species and where the cactus grows. Things like how much water the plant gets or the specific type of cactus can change both the amount of mucilage you get and its overall quality.

According to Brandon et al, mucilage demonstrates distinctive rheological behaviour linked to its unique composition of uronic acids, neutral sugars, and branching side chains. Mucilage structural might differ depending on the source, but in general, it is mostly made up of proteins and carbohydrate [23]. For instance, certain species pack their mucilage

with polysaccharides which increases its content and also helps in good film formation [7]. Understanding these compositional variations is essential for selecting the appropriate cactus source for specific bioplastic applications. Additionally, the extraction methods employed can also impact the purity and functionality of the mucilage obtained.

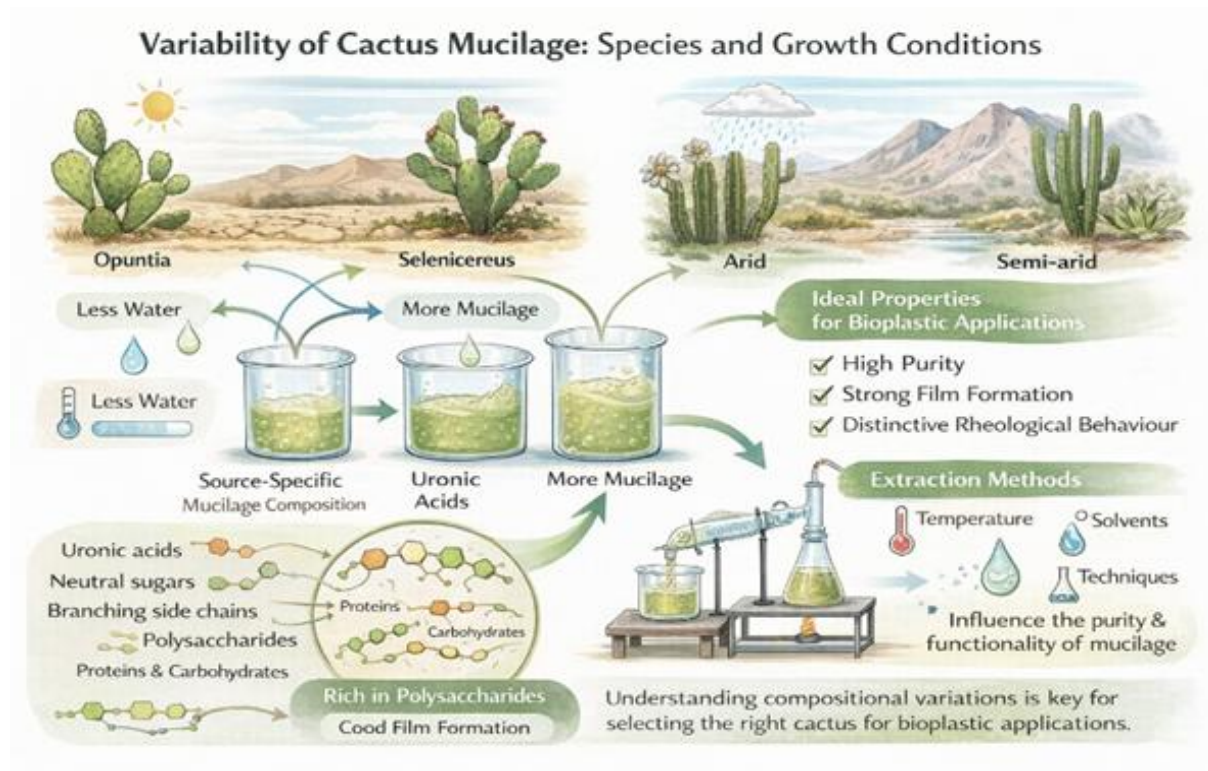


Fig 4: composition and growth conditions of cactus

III. EXTRACTION METHODS

The extraction of mucilage is influenced by various factors, including the species of cactus, the part used, and the method employed. According to [35], traditional and modern methods are used to extract the mucilage. Mucilage can be extracted from any part of the plant is considered a valuable natural polysaccharides source with excellent potential in pharmaceutical and food applications [22].

3.1 Traditional Methods

Traditional methods for extracting cactus mucilage involve mechanical and aqueous processes [11]. One common approach is maceration, where the cactus cladodes are crushed and mixed with water. The mixture is then subjected to agitation, allowing the mucilage to leach into the water. This method is simple and cost-effective but may result in lower yields due to incomplete extraction.

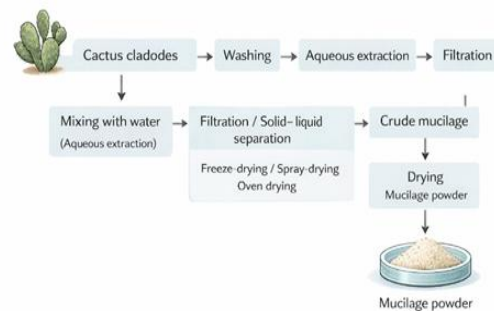


Fig 5 : Mechanical Extraction Flow Diagram of cactus

Another traditional technique is the use of solvents. Ethanol precipitation is frequently employed, where ethanol is added to the aqueous extract to precipitate the mucilage. The precipitate is then separated, washed, and dried. This method can enhance the purity of the mucilage but requires careful control of solvent concentrations to prevent degradation of the mucilage [21].

3.2 Modern techniques

Advancements in technology have led to the development of more efficient extraction methods. Microwave-assisted extraction (MAE) utilizes microwave energy to heat the sample rapidly, facilitating the release of mucilage [10]. This method reduces extraction time and solvent usage, making it more environmentally friendly.

3.2.1 Ultrasound-assisted extraction (UAE) employs ultrasonic waves to create cavitation bubbles in the solvent, enhancing the mass transfer and extraction efficiency. UAE has been shown to yield higher quantities of mucilage in a shorter time compared to traditional methods.

3.2.2 Enzyme-assisted extraction involves the use of specific enzymes to break down the cell walls of cactus cladodes, releasing mucilage [28]. This method can enhance the yield and purity of mucilage while reducing the need for harsh solvents. Enzymes such as cellulases and pectinases are commonly used in this process.

3.2.3 Supercritical Fluid Extraction (SFE) utilizes supercritical fluids, typically carbon dioxide, to extract mucilage [7]. The supercritical state of CO₂ possesses unique properties that allow it to penetrate plant materials and extract mucilage efficiently. This method is environmentally friendly as it eliminates the need for organic solvents.

3.2.4 Membrane filtration methods, including microfiltration and ultrafiltration, are employed to separate mucilage from other components in the cactus extract [21]. These techniques utilize semi-permeable membranes to filter out larger particles, resulting in a concentrated mucilage solution. They are advantageous for producing high-purity mucilage without the use of heat or chemicals.

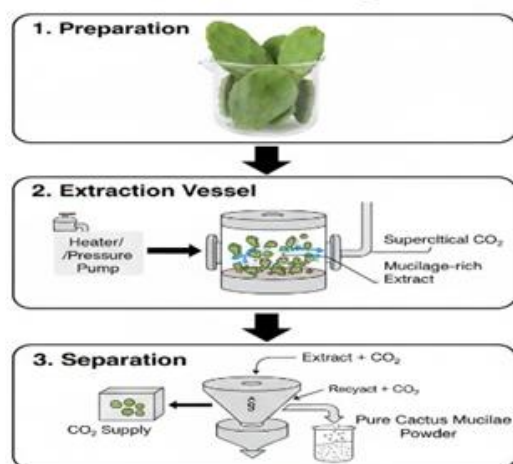


Fig 6 : Supercritical Fluid Extraction setup for Mucilage

Despite the advantages of advanced extraction techniques, challenges remain, such as cost and scalability. Some methods, like SFE, require expensive equipment, and scaling up laboratory methods to industrial levels can be challenging. There is also a need for standardized protocols to ensure consistent quality and yield [21].

Future research should focus on optimizing these methods to make them more cost-effective and scalable, ensuring a sustainable supply of high-quality cactus mucilage [28].

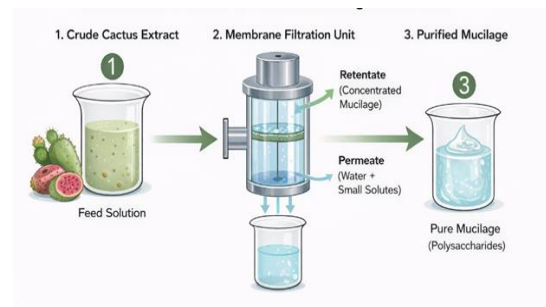


Fig 7: Membrane Filtration setup for concentration of Mucilage

IV. APPLICATIONS OF MUCILAGE

Over the past decades, various typologies of bioplastics have been introduced with the aim of partially replacing plastic products, featuring different properties for a series of possible applications that includes:

4.1 Wound healing

In recent years, interest has grown in using plant-derived mucilage's, especially from *Opuntia ficus-indica* (cactus), to develop wound-healing materials such as hydrogels, films, and dressings [43]. Many review papers point out that these mucilage-based materials are very natural and non-toxic, that are biocompatible, and biodegradable, which makes them suitable for applying directly to damaged skin without irritation. When it is used as dressing, they form a soft, moist, and protective layer over the wound, which helps the tissue repair itself while remaining gentle on the affected area.

The evidence form of clinical and animal studies also supports the healing ability of *Opuntia* polysaccharide extracts. When applied topically,

these extracts have been shown to significantly accelerate re-epithelialization and remodelling of full-thickness wounds [13]. Researchers suggested that this improvement may be caused due to their effect on cell–matrix interactions and the increased presence of important structural proteins like laminin, which plays a major important role in new tissue formation. Many reviews on plant mucilage’s also highlight that their rheological properties, noting that their ability to form shear-thinning hydrogels makes them easy to apply while still keeping the wound moist— which is an essential condition for proper healing.

More recent studies have expanded that on these findings, showing that mucilage does more than just maintain moisture. Several reviews emphasize its anti-inflammatory and immune modulating effects, and supported by results from in vitro experiments and pre-clinical models. These added benefits help promote tissue regeneration, which helps in minimize scarring, and reduce the chances of infection. Altogether, we can consider that the mucilage-based dressings are a promising and natural option for advanced wound care, that perfectly fits with the increasing interest in more sustainable dermatological materials. In Review call of [32], continued research into improving mechanical properties and developing active combinations with antimicrobial or pro-healing agents to create next-generation wound dressings.

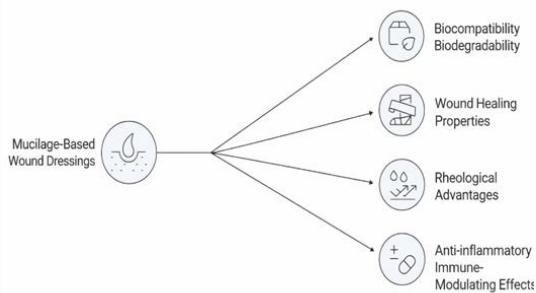


Fig 8: Unveiling the Multifaced Benefits of Mucilage.

4.2 PAPER MANUFACTURING

The paper industry increasingly relies on bio-based polysaccharides as coating binders, surface sizing agents, rheology modifiers, retention aids, and strength enhancers, aiming to replace petroleum-derived latexes without sacrificing runnability or print quality [35]. Recent reviews on paper coatings and papermaking additives describe how polysaccharides such as starch, carboxymethyl

cellulose, alginate, pectin, and plant gums provide the hydrogen-bonding, film-forming, and water-management functions needed at the wet-end and on the paper surface [42][19]. These polysaccharides help with pigment binding, which helps in reduce dusting and picking during printing, and even improve the barrier properties of coated papers, which is especially useful for packaging applications. Overall, it clearly shows a shift toward using natural polymers to achieve good strength and barrier performance while still keeping the paper recyclable and compostable.

Although most of reviews mainly discuss about common polysaccharides such as starch, CMC, and alginate, cactus mucilage from *Opuntia* species also shares similar chemical and rheological characteristics. Dedicated reviews on *Opuntia* mucilage characterize it as a branched, uronic-acid-containing heteropolysaccharide rich in arabinose, galactose, rhamnose, and xylose, with strong water-binding and shear-thinning behaviour [44]. Because of this composition, the mucilage shows stronger water-binding ability and a clear shear-thinning flow behaviour. These properties explain why it forms continuous films when dried and handles well in aqueous dispersions—qualities which are also required for coating binders and surface-sizing formulations. Essentially, the same features that allow *Opuntia* mucilage to perform well in edible films and helps in biodegradable coatings which make it suitable for paper coatings, where hydrogen bonding with cellulose fibers and pigments is necessary.

From a formulation viewpoint, review articles point out that polysaccharide binders must maintain balance between water retention, smooth levelling, and developing sufficient green strength before the sheet enters the dryer. Plant-derived polysaccharides achieve this by offering multiple hydroxyl and carboxyl groups which supports hydrogen bonding, while their molecular weight helps in adjusting viscosity at the high shear rates seen in rod or blade coating. Based on published rheological data, *Opuntia* mucilage shows pseudoplastic behaviour and helps to stabilize water-based dispersions, which suggests it could act as a rheology modifier or binder—either on its own or mixed with starch or CMC. This could help in improving pigment holdout, coat weight uniformity, and pigment packing without the need for synthetic thickeners. This approach closely matches existing practices in

polysaccharide-based coatings and also agrees with the way *Opuntia* mucilage performs in other thin-film systems.

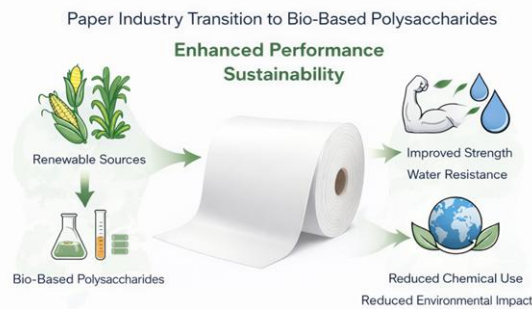


Fig 9: Paper industry transitions to bio-based polysaccharides for enhanced performance and sustainability.

Barrier properties and print performance are major considerations for coated papers. Many Reviews indicate that natural polysaccharide coatings can help in reducing oil and grease penetration, modifying water-vapor transmission, and improving ink setting by altering pore structure and surface energy. While starch remains the most widely used binder, adding gums or pectin-like components can help reduce brittleness and maintain flexibility, especially under low humidity. *Opuntia* mucilage reviews mention its high moisture affinity and flexible film behaviour. therefore, blending it into starch–CMC formulations may reduce coating cracks, provide better gloss during calendaring, and minimise dusting. Since the mucilage contains uronic acids, it can also actively participate in ionic interactions, which can be useful for crosslinking with multivalent salts commonly used in surface-sizing. Review papers also highlight that these interactions can improve wet-rub resistance and reduce offset-setoff issues.

At the wet-end of papermaking, natural polymers are also known to function as retention aids, drainage enhancers, and dry-strength agents by linking fibers, fines, and fillers together. Although cationic starch is the usual choice, reviews show that anionic or neutral polysaccharides can also be used if they are chemically modified—for example, through cationization or carboxymethylation—or paired with aluminium or polyamine coagulants. Since *Opuntia* mucilage contains carboxyl groups and plenty of hydroxyls, some review articles suggest that it can undergo similar modification routes. This means that a mildly cationized cactus mucilage could potentially act as a strength additive

and retention aid, similar to other polysaccharides discussed in wet-end chemistry reviews.

Another practical factor is processability. Reviews note that bio-based binders can lower the VOC emissions and improve worker safety compared to synthetic latexes, but they may be more sensitive to microbial activity and water exposure. To address this, mild crosslinkers (such as citric acid or calcium salts) and nano-fillers (like nanocellulose or layered clays) are often recommended. Interestingly, reviews on mucilage report similar improvements when these strategies are used in food-film applications. Techniques like ionic crosslinking and nanocellulose blending helps to reduce water sensitivity while keeping the materials biodegradable. These same approaches can be transferred to paper coatings to improve wet strength, water resistance, and helps in coating durability while remaining compatible with recycling processes.

Finally, sustainability discussions in papermaking reviews highlight the advantages of bio-based coatings in reducing microplastic release and making end-of-life recycling easier. Majority of Reviews on *Opuntia* mucilage also point out that cactus biomass is abundant in arid and semi-arid regions and is already processed for food or nutraceutical products, which creates convenient side streams for mucilage extraction. This makes cactus mucilage an appealing option for circular bioeconomy models—assuming consistent quality, reliable supply, and proper preservation during transportation and storage.

4.3 COSMETIC

This eco-friendly biopolymer is getting a lot of attention for its potential in various applications in various fields because it works well in so many different ways. One of the best things about it is It can handle UV light without breaking down. so, stuff made from it, like packaging or skincare products, just sticks around longer. It's a big win. Plus, it also gets along with the living cells and tissues, which means you can safely use it in things that touch your skin or even go inside the body. This makes it a great option for products that come into contact with the body, like medical or cosmetic formulations [17].

Another cool thing is its cohesion. If we indicate it in general terms, it helps the products to cling better

on your skin or mucous membranes. This makes it easier for active ingredients to get absorbed, so people end up with treatments or cosmetics that work better and stick around for longer time.

4.4 food package industry

In recent years, the quest for sustainable and eco-friendly food packaging has elevated cactus mucilage—particularly from *Opuntia ficus-indica*—as a viable biopolymer alternative to conventional plastics [35][42]. Many studies and reviews highlight and said that the mucilage can hold large amounts of water, easily form films, and is naturally non-toxic. Because of these properties, it really works well for making biodegradable films and edible coatings that help protect fresh and perishable foods such as meat and fish or dairy products like milk. These films also allow a certain level of breathability and flexibility, which helps in reducing spoilage of food by controlling moisture and gas exchange.

Beyond structural benefits, mucilage films offer functional advantages when blended with other natural biopolymers like starch, agar, or cellulose [35]. This combination produces more water resistance, flexibility and improved mechanical strength, while still keeps the material safe and biodegradable. It doesn't stop there it self some of recent innovations said that by adding bioactive ingredients like essential oils, antioxidants, or probiotics. These additions not only improve the stability of the films but also turn them into active packaging materials that can slow down microbial growth or delay browning, ultimately extending food shelf life. So, food lasts longer, and you get packaging that does more than just wrap a sandwich. Which helps in extending food shelf life

If we look at the research carefully, there's been a real jump in studies on cactus mucilage-based packaging over the last ten years. Scientists and institutions from places like Tunisia, the US, and Europe are really pushing this field forward. They're digging and performing several experiments in this field and finding out how to make the films, how to pull out the mucilage, and how these films hold up in terms of strength and keeping out unwanted moisture or air. All that work paints a pretty convincing picture—mucilage has some real potential in future food packaging

However, there are still some drawbacks. mucilage films aren't perfect. Pure mucilage films are quite hydrophilic which readily absorbs or dissolves in water, can have only moderate or minimum tensile strength, and can lose stability when exposed to moisture frequently. To address these issues, review papers commonly suggest adding plasticisers, mild crosslinkers, or nanofillers, such as nanocellulose or clay particles, to reinforce the films.

Overall, mucilage-based bioplastics can definitely appear to be a promising sustainable option for future food packaging. While research is moving fast, it's not hard to imagine these bioplastics catching up to, or even beating, conventional plastics when it comes to both performance and eco-friendliness. Their natural degradability, safety, and ability to be enhanced with functional compounds make them stronger to replace conventional plastics. With ongoing research and improvements in formulation, these materials in future may become competitive with, or even superior to, traditional plastic packaging.

V.FUTURE PERSPECTIVE

Cactus mucilage has shown a lot of promise such as sustainable biopolymer, and within next few years it could open up even more possibilities [15][7]. However, moving the cactus mucilage from small-scale research to large-scale applications requires many improvements.

In the future, scientists need to work on boosting its strength and barrier properties, introducing it to nanotechnologies, and making it at larger scale, finding different paths to keep the production costs down. With the food industry pushing for more sustainable materials, there's growing interest in biopolymers that make food safer, better for the environment, and higher in quality. These properties translate into its industrial potential as a thickener, stabilizer, and film-forming agent. Factors including structural composition, pH, polymer concentration, extraction methods, and presence of cross-linking agents influences the functional performance of mucilage. Changes in these parameters affects overall ability of binding and gelling potential.

Overall, the future perspective for cactus mucilage is highly encouraging. With continued research, technological improvements, and interdisciplinary cooperation, and it has the potential to evolve from

a promising natural extract into a widely used, eco-friendly biopolymer for multiple industries

VI.CONCLUSION

Cactus mucilage has emerged as a promising plant-derived biopolymer with significant potential in sustainable material development. Its heteropolysaccharide composition, excellent water-binding capacity, and natural film-forming ability make it suitable for applications such as biodegradable food packaging, wound dressings, paper coatings, and cosmetic formulations. These functional properties, combined with its non-toxicity and biodegradability, position mucilage as an attractive alternative to petroleum-based plastics.

However, limitations such as high moisture sensitivity, moderate mechanical strength, and challenges in large-scale extraction still restrict its widespread industrial use. Current research shows that these issues can be addressed through plasticization, cross-linking, blending with other biopolymers, and incorporation of nanofillers, which improve mechanical stability and barrier performance.

Overall, cactus mucilage represents a sustainable and versatile biopolymer aligned with circular economy goals. With further advancements in material modification, process standardization, and industrial-scale production, it has strong potential to become an important component of next-generation eco-friendly materials.

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