

Exploring the Versatile Applications of Almond Gum Through Crosslinking Reactions: A Comprehensive Review

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Abstract

Almond gum, a natural polysaccharide obtained from the exudate of *Prunus dulcis*, is drawing considerable interest due to its inherent biodegradability, biocompatibility, and multifunctional characteristics. As a plant-derived polymer, it offers a sustainable and eco-friendly alternative to synthetic materials in a variety of applications. This review highlights the growing utility of almond gum, particularly focusing on its crosslinking behavior using different agents such as glutaraldehyde, carbodiimides, gelatin, sodium caseinate, polyacrylic acid, and periodate-oxidized sugars. These crosslinking agents significantly enhance the mechanical strength, thermal stability, and water resistance of almond gum-based materials, making them more durable and suitable for practical uses. Such chemically modified forms of almond gum are increasingly used in the pharmaceutical and biomedical sectors, as well as in food processing and environmental applications. Furthermore, the development of polyelectrolyte complexes involving almond gum has opened up promising avenues in advanced drug delivery systems, tissue engineering frameworks, and water purification technologies. These complexes improve the functional versatility of almond gum, allowing it to serve as a carrier, stabilizer, or scaffold in various formulations. Modern research supports the wide-ranging potential of almond gum across disciplines including medicine, agriculture, environmental management, and food science. Its natural origin, combined with its functional adaptability, positions it as a smart and sustainable choice. This review consolidates current advancements and industrial prospects, emphasizing almond gum's role as a valuable, eco-conscious material for next-generation polymer applications.

Keywords: Natural polysaccharide, Crosslinking agents, Drug delivery, Biocompatibility, Sustainable polymer, Environmental applications, Biomedical applications

Abbreviations

AG: Almond Gum, **C=N:** Schiff Base, **CHO:** Aldehyde Group, **COOH:** Carboxyl Group, **EFSA:** European Food Safety Authority, **FDA:** Food and Drug Administration, **FTIR:** Fourier Transform Infrared Spectroscopy, **GA:** Glutaraldehyde, **H₂O:** Water, **NaOH:** Sodium Hydroxide, **NH₂:** Amine Group, **PAA:** Polyacrylic Acid, **PEC:** Polyelectrolyte Complex, **PVA:** Polyvinyl Alcohol, **R&D:** Research and Development

1. Introduction

The natural polysaccharide substance known as badam pisin, which is derived from the exudates of the *Prunus dulcis* sweet almond tree, is commonly referred to as almond gum. This natural gum consists primarily of a carbohydrate mixture composed of L-arabinose, D-galactose, and uronic acids. The molecular weight of almond gum exceeds 15 million g/mol, which contributes significantly to its highly hydrophilic nature and its capacity to form gel-like structures in aqueous environments. Due to these unique structural and physicochemical properties, almond gum has found a wide range of applications across multiple industries, including the food industry, pharmaceutical formulations, and cosmetic products. ²

In food products, almond gum serves several vital roles: it acts as a texture enhancer, helps extend shelf-life, stabilizes formulations, and functions effectively as an emulsifying agent. Within the food processing sector, manufacturers incorporate almond gum in various formulations such as ice cream, where it helps prevent the formation of ice crystals during freezing, thus improving consistency. Similarly, it is used in baked goods to enhance overall texture and sensory attributes. These applications are supported by multiple scientific studies that have demonstrated almond gum's efficiency as a stabilizing agent in emulsion systems, contributing to better product uniformity and quality.

Beyond its functional roles in food, almond gum also provides numerous health-related benefits. It is

recognized as a natural prebiotic substance, meaning it can support intestinal health by promoting the growth and activity of beneficial gut bacteria. Additionally, it plays a role in helping regulate metabolic processes within the body. Current research data show that almond gum positively supports normal gut microbiota by encouraging the proliferation of healthy bacterial strains. However, it is important to note that much of this evidence has been obtained from animal model experiments, and there is currently a limited amount of data derived from human clinical studies.

In order to achieve stable elastic properties and adequate mechanical resistance, almond gum often undergoes crosslinking reactions. Several treatment approaches have been explored to modify its properties, including the application of heat, exposure to radiation, and chemical crosslinking with agents such as glutaraldehyde or treatment with calcium ions. These methods have been studied in detail to evaluate their effectiveness in improving almond gum's structural performance in different applications.

One of the key advantages of almond gum lies in its eco-friendly and sustainable nature. As a naturally occurring polymer, it decomposes without causing environmental harm, making it a promising alternative to synthetic polymers. Life cycle assessment (LCA) studies have demonstrated that almond gum exhibits a lower environmental footprint across its lifecycle compared to synthetic polymeric materials, reinforcing its status as a green material choice.

Furthermore, the inclusion of almond gum in food products has received approval from regulatory authorities such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). These approvals ensure that the use of almond gum in commercial food products meets established safety and quality standards, thereby protecting consumers and maintaining industry compliance.

Despite its promising attributes and potential for widespread application, the broader adoption of almond gum faces several limitations. One of the primary barriers is the difficulty associated with large-scale production, which affects its economic feasibility. Additionally, the cost of almond gum remains relatively high in comparison to synthetic alternatives, and its availability in sufficient quantities remains a challenge in many regions.²

This study explores and reviews the most recent developments in almond gum research. It focuses on its chemical structure, industrial uses, health-related advantages, polymerization methods, environmental impact, and regulatory approval in the context of food safety. However, there is a significant need for further research, particularly involving human clinical trials, to validate its health benefits conclusively. Additionally, more extensive investigations are required to explore and expand the pharmaceutical applications of almond gum, which remain underdeveloped at present.

2. Chemical composition and structure

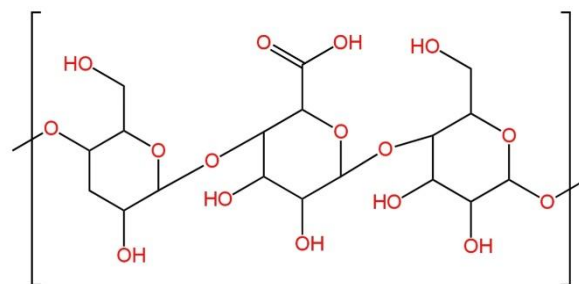


Figure 1.1: Structure of Almond gum²⁷

The main components of Almond gum consist of polysaccharides which include L-arabinose (46.83%) and L-galactose (35.49%) and uronic acids (5.97%) alongside minimal quantities of D-mannose, rhamnose, and glucose. The gum structure consists of 2.45% proteins and 0.85% fats together with sodium, potassium, magnesium, calcium, iron and other essential minerals. Polysaccharide chains create a hydrophilic complex network through their connections via glycosidic bonds. The network structure enables almond gum to serve essential functions in food and pharmaceutical items and cosmetics by working as a powerful emulsifier and substance thickener and stability provider.²⁷

3. Physicochemical properties

Almond gum exhibits a range of valuable physicochemical properties that contribute to its broad applicability in industrial and pharmaceutical formulations. It is primarily composed of 92.36% carbohydrates, with minor amounts of proteins (2.45%) and fats (0.85%), highlighting its natural polysaccharide-rich profile. The predominant sugars present include arabinose (46.83%), galactose (35.49%), and uronic acid (5.97%), along with trace amounts of mannose, rhamnose, and glucose. These sugar constituents play a critical role in its gelling, binding, and emulsifying behavior. Almond gum is also a source of essential minerals such as sodium, potassium, calcium, magnesium, and iron, which may contribute to its nutritional and functional properties. One of its most notable features is its high water absorption capacity, which enhances its utility in formulations requiring moisture retention or swelling characteristics. It demonstrates strong emulsifying capacity, with optimal stability observed at an 8% w/w concentration and within a pH range of 5.0 to 8.0. Notably, almond gum has extremely low foaming capacity, making it particularly suitable for applications where minimal foam formation is desired. Its thermal stability improves with increased gum content in composite materials, indicating its potential in thermally processed products. Furthermore, almond gum exhibits good mechanical strength when used in composites and displays favorable barrier and solubility properties, making it an effective natural polymer in the development of stable and functional biopolymeric systems.

Here is a chart summarizing the physicochemical characteristics of almond gum:

Table 1.1: Physicochemical properties of Almond gum ²⁹

Characteristic	Value/Description
Composition	92.36% Carbohydrates, 2.45% Proteins, 0.85% Fats
Main Sugars	Arabinose (46.83%), Galactose (35.49%), Uronic Acid (5.97%), Traces of Mannose, Rhamnose, and Glucose
Minerals Present	Sodium, Potassium, Calcium, Magnesium, Iron
Water Absorption	High water absorption capacity
Emulsifying Capacity	Most stable emulsion at 8% w/w concentration and pH 5.0 to 8.0
Foaming Capacity	Extremely low foaming capacity
Thermal Stability	Degradation temperature increases with higher almond gum content in composites
Functional Properties	Good mechanical strength in composites, low barrier and solubility characteristics

4. FTIR analysis

Fourier Transform Infrared Spectroscopy (FTIR) is a powerful analytical tool used to study the chemical structure and functional groups of almond gum and its crosslinked derivatives. FTIR analysis provides insights into the molecular interactions and structural changes that occur during crosslinking reactions. This section discusses the FTIR spectra of almond gum, supported by relevant examples and citations.

In the FTIR spectrum of native almond gum, a broad absorption band appears around 3300–3400 cm^{-1} , corresponding to the O–H stretching vibrations of hydroxyl groups, which are abundant due to the gum's polysaccharide composition. A characteristic peak near 2920 cm^{-1} is attributed to C–H stretching of aliphatic chains, while a band near 1600–1650 cm^{-1} reflects asymmetric stretching of carboxylate groups (COO^-), commonly associated with uronic acid residues. The region between 1000–1200 cm^{-1} shows intense bands due to C–O–C and C–O–H stretching vibrations, which confirm the glycosidic linkages and backbone structure of the polymer ²

When almond gum is crosslinked with chemical agents such as sodium trimetaphosphate (STMP), new peaks and shifts in existing bands occur, indicating successful modification. For example, a new band observed around 1230–1250 cm^{-1} is associated with the P=O stretching of phosphate ester groups, confirming crosslinking with STMP. The decrease in intensity of the O–H band suggests hydroxyl groups are actively involved in the esterification process. In certain crosslinked formulations, a peak around 1720–1735 cm^{-1} corresponding to C=O stretching from ester linkages may appear when citric acid or similar agents are used.

Blending almond gum with other biopolymers also alters its FTIR profile. In almond gum–chitosan composites, studies have reported a shift or broadening of bands in the 1500–1650 cm^{-1} region, indicating electrostatic interactions between carboxyl and amino groups. These spectral changes support the formation of polyelectrolyte complexes, enhancing the structural integrity of the final product. Thus, FTIR serves as a vital technique for confirming the functional modifications, compatibility, and molecular stability of almond gum in both native and chemically altered forms. ²

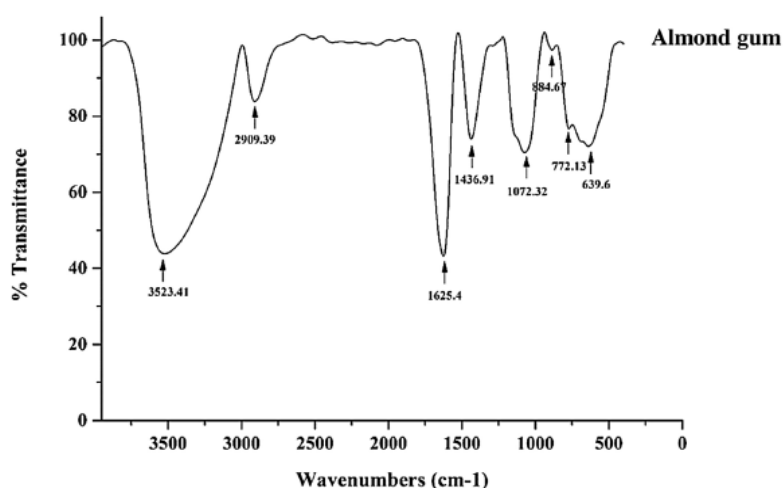


Figure 1.2: FTIR analysis of AG ²

Table 1.2: FTIR Peaks of AG ²

Functional group	Peaks
OH stretching vibration	3523.41
C H stretching of CH ₂ group	2909.39
COOH stretching	1625.4, 1436.91
(1-4), (1-6) linkage of galactose & mannose	772.13
Galactose and mannose	884.6

5. Extraction procedure

Almond gum serves multiple functions in medicine and food production as well as adhesive applications since centuries. The extraction technique has progressed with time beginning with hand-harvesting methods towards contemporary techniques that improve both yield and extraction purity.

5.1 Ancient or traditional methods

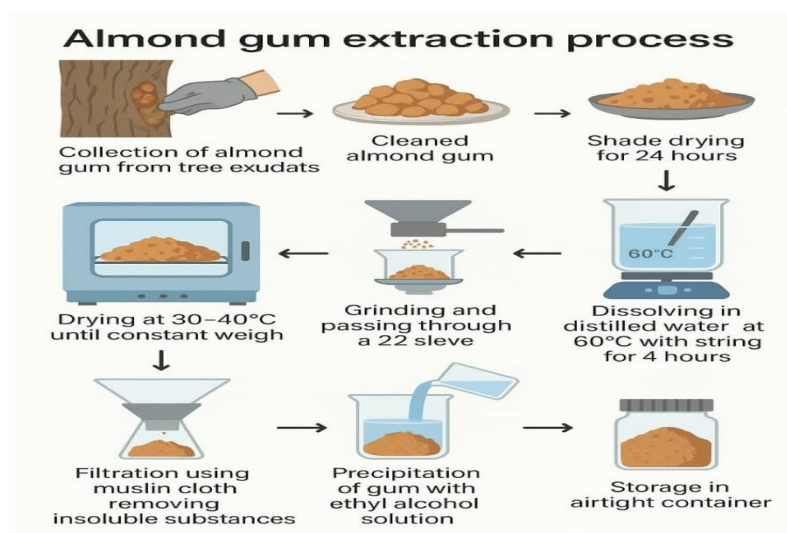
The extraction of almond gum mainly relied on traditional extraction methods during ancient periods. Natural gum extraction from almond tree bark required farmers to either leave the wounds to develop gum on their own or introduce controlled cuts to activate gum production. The method of tapping was a frequent practice in almond tree growing territories. After two to three weeks of air exposure the gum substance would harden and workers would gather it manually. The collected gum underwent cleansing with water before drying under sunlight for later use.³² The lack of advanced purification methods blocked almond gum from achieving refined status so it got primarily used as a raw substance in traditional medicine and local food preparation and as an adhesive.

5.2 Modern or current methods

The modern extraction method of almond gum uses advanced ingredients together with specific instruments to reach superior process results and higher product purity. The advanced processing methods utilize ethyl

alcohol for gum identification and petroleum ether for separating oil from the extraction products. The combination of these solvents leads to increased purity of end products through effective impurity separation. A hot air oven allows precise temperature-controlled drying between 35-45°C and digital pH meters enable scientists to perform accurate quality evaluations. The use of stalagmometers helps measure surface tension because this property affects how well gum material binds. The removal of particles becomes more efficient when using muslin cloth or Whatman filter paper for filtration. Steps involved in extraction of almond gum: ¹³

- ✓ Preparation starts with a collection of almond gum from tree exudates which goes through a complete cleaning process for removing debris and impurities.
- ✓ The drying procedure includes first shade-drying the cleaned gum for 24 hours before exposing it to heat between 30-40°C until it reaches a constant weight. A grinder combines the dried gum into a small powder which subsequently passes through a sieve with a number #22.
- ✓ The powder extraction process includes dissolving almond gum (*Prunus dulcis*) in distilled water at 60°C temperature under continuous stirring for 4 hours. A filtration process using muslin cloth removes the insoluble substances from the mixture.
- ✓ The filtrate leads to precipitation of gum after addition in ethyl alcohol solution. A muslin cloth strains the precipitate following which the researcher performs ethyl alcohol washes then filters the solution.
- ✓ The dried gum product needs hot air oven treatment at 35-45°C until it reaches its final weight.
- ✓ The almond gum requires petroleum ether defatting treatment that spans four to five hours. The filtered solution needs additional drying at 45°C.
- ✓ The dried and powdered almond gum requires storage in airtight containers for pharmaceutical or other application purposes.

**Figure 1.3: Almond gum extraction process**

With the implementation of contemporary purification methods the purity level of almond gum reaches higher standards through thorough impurity elimination. Through the application of high-speed spinning centrifugation behaves as a commonly utilized method that enables density-based separation from impurities to yield a cleaner gum extract. Ultrasonication contribution to the purification process involves both size-reduction of large particles and impurity dispersion which results in better clarity and purity. When combined with specific enzymes that deactivate unwanted compounds through decomposition the gum becomes more appropriate for pharmaceutical and food and cosmetic industry usage. Advanced techniques enable both a significant increase in high-quality almond gum output and consistent reliable performance in multiple industrial sectors.^{5, 21}

6. Crosslinking reaction

6.1 Almond gum and glutaraldehyde

The main reaction process of almond gum (AG) and glutaraldehyde (GA) involves creating crosslinkages between the two components. The bifunctional aldehyde glutaraldehyde exists with two reactive carbonyl (-CHO) groups which make it efficient for crosslinking applications. The polymer network stabilizes through covalent bonds which form when almond gum reacts with its hydroxyl (-OH) groups. The reaction strengthens both the mechanical strength and thermal stability and water resistance features of almond gum.

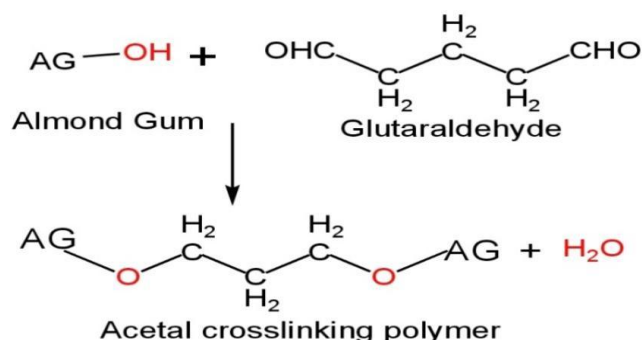


Figure 1.4: Chemical reaction of AG and Glutaraldehyde

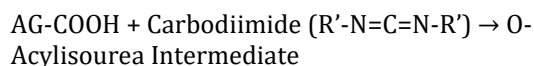
The hydroxyl moieties in almond gum join carbonyl from glutaraldehyde through addition chemistry into condensation which results in ether/acetal bonds. During the reaction water is released as a result.

Through this reaction a strong biodegradable hydrogel or film emerges which demonstrates better elasticity and water resistance and increased tensile strength. These materials find application in biomedical fields and drug delivery systems as well as wound dressing methods.²⁵

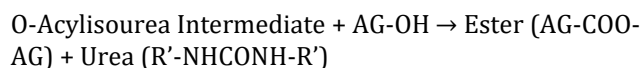
6.2 Almond gum and Carbodiimides

The crosslinking agent carbodiimide has broad industrial use because it enables both amide and ester bond creation. Carbodiimide chemistry allows the formation of covalent bonds that connect carboxyl (-COOH) carrying almond gum molecules through its reaction with AG.⁵⁰

Step 1: Activation of Carboxyl Groups



Step 2: Crosslinking with Hydroxyl group



The first step of the reaction activates almond gum carboxyl groups through carbodiimide treatment to create a reactive O-acylisourea intermediate. The generated intermediate enables connection to hydroxyl groups before forming ester bonds. The reaction produces urea that behaves as a non-harmful chemical which easily removes from the system.

Carbodiimide-crosslinked almond gum finds multiple applications as a drug delivery element for controlled release and as a tissue engineering material for biomedical usages and wound covering and also functions in food packaging to resist moisture entry. The material provides purification services for water systems in addition to its agricultural applications because it operates as an eco-friendly substance.

6.3 Almond gum and gelatin

A crosslinked network system between almond gum (AG) and gelatin occurs through covalent and ionic bonds that become possible through the inclusion of crosslinking agents such as glutaraldehyde and carbodiimide. The chemical interaction occurs between the hydroxyl (-OH) groups of AG with amino (-NH₂) groups of gelatin which leads to persistent bonds.

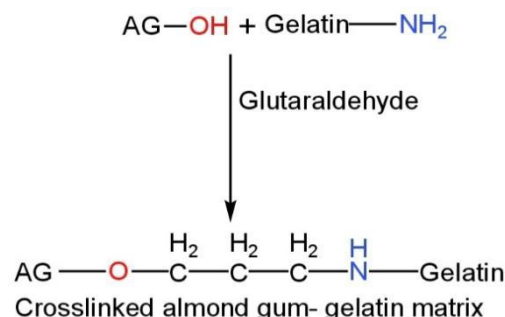


Figure 1.5: Chemical reaction between AG and Gelatin

A polymer network with a three-dimensional structure develops from the chemical reaction that combines almond gum hydroxyl groups with gelatin amino groups. The material becomes stronger and more temperature-resistant and better suited for biological applications due to this new arrangement.

The three-dimensional polymer structure of crosslinked almond gum-gelatin serves medicinal purposes through sustained-release drug delivery systems as well as wound dressing applications and tissue engineering scaffolds due to its biocompatible nature. This material finds applications in food packaging since it shows both degradation capabilities and resistance against moisture damage.⁴⁶

6.4 Almond gum and sodium caseinate

Electrostatic bonding together with hydrogen bonding and hydrophobic forces enables almond gum (AG) to complex with sodium caseinate which originates from milk. The functional properties of biopolymer complexes and hydrogels benefit significantly when AG interacts with sodium caseinate.

$\text{AG-COO}^- + \text{Na-Caseinate-NH}_3^+ \rightarrow \text{AG-Caseinate Complex}$

A polyelectrolyte complex forms when the carboxyl groups of almond gum accept sodium caseinate amino groups due to their opposite charges while avoiding the requirement for extrinsic crosslinking agents.

The reaction depends on ionic bonding between functional groups possessing opposite charges between almond gum and sodium caseinate. Hydrogen bonds together with hydrophobic forces help create a stable three-dimensional network. The complex structure provides additional mechanical strength and both water retention capabilities and biocompatible properties to the material.

Food industry utilizes almond gum-sodium caseinate complex as a versatile ingredient that works as stabilizer along with being an emulsifier and thickener. The substance finds application in drug delivery technologies as well as biodegradable films and edible coatings where it enhances their protective capabilities.⁴⁰

6.5 Almond gum and Polyacrylic acid (PAA)

The reaction conditions determine whether Almond gum (AG) and polyacrylic acid (PAA) will create polyelectrolyte complexes or engage in covalent crosslinking. The carboxylic acid groups found abundantly in PAA (COO-H) interact with the hydroxyl (OH) and carboxyl (COO-H) groups of almond gum through ionic and hydrogen bonding mechanisms.

These complexes between Almond gum and polyacrylic acid find application in drug delivery systems because they maintain both controlled and sustained release properties through their hydrophilic nature. These materials find usage in wound treatment applications as well as personal hygiene products that utilize hydrogels to moisturize the skin. Due to their biodegradable and biocompatible nature these materials are particularly appropriate for agricultural usage as soil conditioners.²⁰

6.6 Almond gum and periodate-oxidized sugars

Almond gum (AG) forms Schiff base or acetal reactions with periodate-oxidized sugars including periodate-oxidized dextran or starch. The periodate oxidation process specifically breaks the C-C linkage connecting vicinal diols present in sugars which creates aldehyde function (-CHO). The almond gum's hydroxyl group forms covalent bonds with the aldehyde groups that exist after periodate oxidizes sugar.

$\text{AG-OH} + \text{Oxidized Sugar-CHO} \rightarrow \text{AG-O-(CH-O)-Sugar} + \text{H}_2\text{O}$

Almond gum-periodate oxidized sugar hydrogels serve as wound dressing components to aid both moisture control and promote rapid healing processes. The materials serve two functions in the development of drug

delivery platforms for controlled substance release and the creation of biocompatible tissue engineering scaffolds. These materials find applications in food packaging to deliver biodegradable films which present increased mechanical performance.

6.7 Almond gum and PVA

The crosslinking between almond gum (AG) and polyvinyl alcohol (PVA) occurs through hydrogen bonding and covalent interactions due to the abundance of hydroxyl (-OH) groups in both biopolymers. These interactions create a stable, biodegradable composite suitable for packaging and biomedical uses. The hydrogen bonding improves compatibility, mechanical strength, and water resistance.

A potential covalent crosslinking can occur via glutaraldehyde, which reacts with the hydroxyl groups in both AG and PVA:

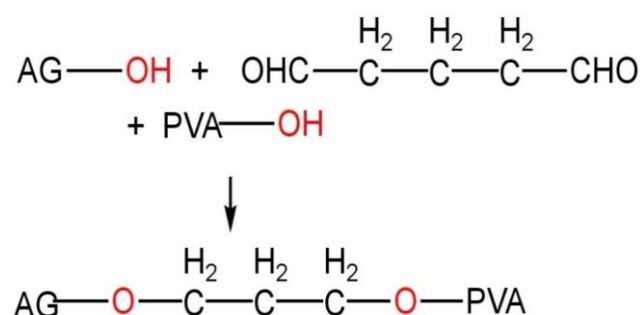


Figure 1.6 Chemical reaction between AG and PVA

The FTIR spectra of AG:PVA composite showed key vibrational bands:

Table 1.3 FTIR spectra of AG and PVA crosslink polymer²⁷

Wavenumber (cm ⁻¹)	Functional group
3415	O-H stretching of AG and PVA
2924	Asymmetric -CH stretching (AG + PVA)
2855	-CH stretching of PVA
1727	C=O stretching (AG and PVA)
1623	Carboxyl group of AG
1422	Symmetric stretch of uronic acid (AG) + CH ₂ stretch (PVA)
1056	Alcoholic group stretch (AG) + C-O-C stretch (PVA)

These peaks confirm hydrogen bonding and functional group overlap, indicating interpolymer compatibility and successful blending.

The AG:PVA composite bioplastic shows excellent potential for eco-friendly packaging applications. It offers improved tensile strength (3.79 MPa), reduced moisture content (10.47%), and lower water solubility (34%), making it suitable for moisture-resistant

packaging. Its strong antibacterial activity against *Pseudomonas* and *Streptococcus* supports its use in food packaging. Moreover, with 43% biodegradability in 15 days, it serves as a sustainable alternative to synthetic plastics.²⁷

7. Applications

Almond gum attracts rising interest because of its biological breakdown and its use suitability throughout several industrial fields. Almond gum applications can be organized into three main classes due to its behavior with other materials, including simple applications, synthetic applications, and polyelectrolyte complex-based applications. Almond gum demonstrates various functional properties through stable systems in these different applications. Its natural origin, non-toxic profile, and excellent biodegradability make it an ideal candidate for industries aiming to replace synthetic polymers with environmentally friendly alternatives. In simple applications, almond gum is often used as a thickening agent, emulsifier, stabilizer, and binder in food and pharmaceutical formulations. In synthetic applications, it can be chemically modified or blended with other polymers to create hydrogels, films, and controlled-release matrices, improving performance characteristics such as tensile strength, moisture retention, and thermal stability. In polyelectrolyte complex-based applications, almond gum interacts with oppositely charged biopolymers to form stable complexes that are highly valuable in advanced drug delivery systems, wound dressings, and nanoencapsulation technologies. Moreover, its compatibility with bioactive molecules and its mucoadhesive properties enhance its utility in site-specific and sustained-release drug delivery. As research into natural polymers continues to evolve, almond gum is increasingly recognized not just as a traditional excipient, but as a multifunctional material with broad potential in emerging technologies.

7.1 Simple applications

The use of almond gum as an independent agent happens in combination with other natural gums such as guar gum or xanthan gum and acacia gum. *Jimmings* which combine with almond gum functions strengthen its viscosity behavior and gelation properties while performing emulsification tasks. Pharmaceutical industries extensively use almond gum blends as tablet-forming binding agents because they deliver targeted drug delivery systems while functioning as protective elements for product stability. These mixtures function exceptionally well as stabilizers along with serving as suspending agents in various liquid formulations which include syrups and emulsions.

When almond gum combines with natural gums in food applications it improves the texture qualities and oral sensations of dressing sauces and dairy dessert products. The mixture absorbs and retains water and its thickening power strengthens soups and gravies while stopping ingredients from dividing. The use of almond gum in low-fat product formulations allows formulators to achieve rich mouthfeel while eliminating excess calories from

their products. Almond gum functions perfectly as a protective agent against ice crystals therefore becomes a vital component for creating ice creams and frozen desserts.

Almond gum enhances cosmetics through double functionality since it stabilizes while acting as an emulsifier within lotions and creams and gels. Almond gum enhances skincare product moisturizing benefits through its protective water barrier function which also soothes the skin surface. Almond gum functions in hair care products to enhance the applicability of shampoos and conditioners and styling products by maintaining their ideal consistency. The film-forming properties from traditional medicine systems apply natural almond gum to make effective herbal pastes and topical wound care products.

Research by Mahfoudhi et al 2014 proved almond gum functions as a suitable wall for β -carotene encapsulation through offering protection while providing affordable gum arabic alternative²⁹. According to Reshma et al 2021 almond gum showed promise as a vegetarian natural substitute for capsule films because it offers therapeutic advantages besides its potential use as a wall material⁴¹. Dhaka et al 2021 achieved enhanced properties within edible films through their combination of almond gum with guar gum which was refined using microfluidization methods¹¹. The development of sustained release pellets through Kanteti et al 2022 involved almond gum as a spheronizing agent while they incorporated gelucire for controlled drug delivery systems²³. Vadivel et al 2018 conducted research which proved almond gum effectiveness as an organic pharmaceutical formulation thickener by evaluating its impact on ororetentive jellies' stability and viscosity⁴⁷. Hedayati et al 2023 studied how wheat starch benefits from the combination of almond and Persian gums which enhances water absorption and pasting properties leading to improved food texture¹⁹.

7.2 Synthetic applications

The production of advanced materials with superior functional properties and mechanical behavior occurs through almond gum crosslinking reactions with chemical agents in synthetic applications. Various materials produced from almond gum utilize crosslinking agents which include glutaraldehyde together with polyvinyl alcohol (PVA) and carbodiimides and gelatin. The crosslinked products demonstrate high water intake together with enhanced structural durability and long-term stability which makes them suitable for pharmaceutical and biomedical sectors and environmental applications.

The drug delivery method utilizes crosslinked almond gum hydrogels designed for controlled sustained drug delivery. Due to its hydrophilic properties almond gum enables drug compounds to diffuse gradually which extends their therapeutic levels in time. The hydrogels show excellent utility in transdermal patches and wound dressings because they create a moist environment leading to speedier healing. Crosslinked films together with nanoparticles allow doctors to release specific

medications with exact precision to desired areas in the human body.

The application of crosslinked almond gum hydrogels shows continuous growth potential in tissue engineering field. Crosslinked almond gum displays two key features that enable it to function as a biological scaffold for cell growth and tissue development. These hydrogels function as suitable platforms when combined with growth factors and biomolecules to help healing processes for damaged tissues. Crosslinked almond gum materials demonstrate effective adsorption potential when used as environmental wastewater remediation agents for heavy metal and pollutant removal in sustainable waste management systems.

The research team of Kaur et al. 2025 created a sustained-release Empagliflozin hydrogel system utilizing almond and neem gums which were crosslinked through glutaraldehyde treatment to boost stability and control drug release processes²⁵. Zare et al. 2024 research provide a review about antimicrobial gum nanocomposites that utilize carbodiimide chemistry for biomedical applications in sustainable technology development⁵⁰. Suresh et al. 2022 designed almond gum/alginate composites which increased tomato shelf-life by improving barrier resistance and antimicrobial properties⁴⁶. Kassozi et al. 2018 developed almond gum-shellac nanoparticles filled with quercetin as they produced significant enhancement of antioxidant capability together with improved bioavailability in a new delivery system for nutraceuticals²⁴. Rahimi et al. 2021 performed research on fish oil emulsions stabilized through bitter almond gum-sodium caseinate conjugates to enhance both stability against oxidation and digestibility of lipids⁴⁰. Fish gelatin obtained superior emulsifying foaming and antioxidant properties through the water-soluble fraction of bitter almond gum conjugation by Bostar et al. 2020 for food applications³.

7.3 Polyelectrolyte based applications

PECs develop from the reaction of almond gum toward chitosan, gelatin or carrageenan and oppositely charged polymers. The properties of these complexes include improved stability as well as enhanced bioadhesiveness and selective permeability features which make them valuable in pharmaceutical applications and food preservation and environmental solutions.

The pharmaceutical application uses almond gum-based PECs to protect sensitive drugs and bioactive compounds during encapsulation. Drug protection together with controlled release occurs through electrostatic almond gum-polymer interactions which form a protective matrix. The systems prove ideal for administering drugs with poor solubility since they enhance availability and drug efficacy. PECs serve as effective tools for delivering medications to designated tissues or organs thereby minimizing drug circulation through the entire body and increasing patient willingness to adhere to their treatments.

Food packaging makes extensive use of PECs based on almond gum because these materials function as degradable edible films. Through their role as natural

protective barriers almond gum-based PECs stop water loss while preventing oxygen entry and microbial contamination in order to increase food preservation times. The incorporation of PECs into functional food formulations enables the protection of probiotics and vitamins and antioxidants through encapsulation when stored and digested.

The applications of PEC developed from almond gum include wastewater treatment due to their use as flocculants. The charged nature of PECs facilitates the aggregation and removal of suspended particles, heavy metals, and organic pollutants from industrial effluents. The environment benefits from water purification operations because almond gum PECs demonstrate both biodegradability and non-toxic properties.

Kumar et al. 2024 developed a biodegradable almond gum-polyvinyl alcohol biopolymer blend for eco-friendly packaging applications, demonstrating improved mechanical strength and water resistance²⁷. Ghaedi et al 2021 investigated almond gum-soy protein isolate conjugates for oil-in-water emulsions, showing enhanced physical and oxidative stability through Maillard conjugation¹⁴. Singh et al. 2022 synthesized almond gum-polyacrylic acid hydrogels loaded with hydrocortisone for colon inflammation treatment, highlighting sustained drug release and biocompatibility⁴⁵. Hussain and Jaisankar 2017 formulated a novel almond gum-polyacrylamide hydrogel-silver nanocomposite, revealing antibacterial activity and enhanced swelling properties²⁰. Venkatesan et al. 2021 developed chitosan-almond gum composites with improved mechanical strength, thermal stability, and antimicrobial properties, making them ideal for compostable food packaging⁴⁸.

7.4 Miscellaneous applications

The established pharmaceutical and food and biomedical applications of almond gum expand into new miscellaneous fields and emerging opportunities. Plant cultivation benefits from almond gum because its water-absorption capabilities allow it to improve soil quality and manage moisture retention in dry areas. The substance acts as a delivery medium for controlled pesticide and herbicide and fertilizer products to reduce environmental risk from these agricultural chemicals. Packaging companies are transforming almond gum into sustainable biodegradable biomaterials for use as plastic alternative coatings which retain moisture and minimize environmental waste.

The adhesive properties of almond gum function together with its film-forming capabilities to make pathways for eco-friendly glue production and paper product manufacturing. Textile manufacturers employ almond gum as a finishing agent for textiles where it enhances fabric strength and delivers non-harmful replacement solutions instead of synthetic additives. Companies use almond gum's natural properties and stabilizing functions to enhance cosmetics and personal care products like moisturizers and gels together with face masks as well as shampoos by providing improved texture and spreadability and extended lifespan.

Almond gum demonstrates increasing utility in environmental markets through its use as a natural flocculating agent within wastewater treatment systems which helps aggregate and extract both particles along with dyes and heavy metals from industrial discharge waters.

8. Conclusion

The multiple properties of almond gum including biodegradability with biocompatibility and versatility in functionality qualify it as a promising material for multiple applications. By applying crosslinking mechanisms almond gum experiences substantial improvements in strength and both thermal properties and water absorption capabilities. The functional applications of almond gum include its successful use in drug delivery systems as well as wound dressings and tissue engineering scaffolds and food packaging materials. The polyelectrolyte complex formation property of almond gum enables new approaches for targeting drugs and treating polluted water. The future development of sustainable applications and optimal crosslinking methods for almond gum will make it a preferred eco-friendly material in pharmaceuticals and biomedical sectors along with environmental conservation work.

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