



## NEXT GENERATION GREEN BIO-ADHESIVES AS RENEWABLE ALTERNATIVES TO SYNTHETIC PETRO-ADHESIVES

Kabita Bist<sup>1</sup>, Sirisha G.C.<sup>1</sup>, Jaga Nath Bashyal<sup>1</sup>, Sumita Subedi<sup>2</sup>, Ralf Lach<sup>3</sup>, Michael Nase<sup>4</sup>, Jagadeesh Bhattarai<sup>1</sup>, Netra Lal Bhandari<sup>1\*</sup>

<sup>1</sup>Central Department of Chemistry, Tribhuvan University, Kirtipur, Kathmandu, Nepal

<sup>2</sup>Department of Chemistry and Chemical Engineering, Inha University, Incheon, South Korea

<sup>3</sup>Polymer Service GmbH Merseburg, Geusaer Strasse 81f, 06217 Merseburg, Germany

<sup>4</sup>Institute for Circular Economy of Bio:Polymers (ibp) at Hof University of Applied Sciences, Alfons-Goppel-Platz 1, 95028 Hof, Germany

\*Correspondence: [netra.tu.edu@gmail.com](mailto:netra.tu.edu@gmail.com)

(Received: April 15, 2026; Revised: May 30, 2026; Accepted: June 17, 2026)

### ABSTRACT

Growing environmental concerns associated with petroleum-based synthetic adhesives, including toxicity, non-renewability, volatile organic compound emissions, and formaldehyde-related health risks, have accelerated the development of sustainable bio-based adhesive systems. This review summarizes recent advances in adhesives derived from renewable resources such as lignin, tannins, proteins, polysaccharides, and vegetable oils. Particular emphasis is placed on adhesion mechanisms, chemical and enzymatic modification, nanotechnology-assisted reinforcement, and self-bonding approaches that can improve mechanical strength, thermal stability, and water resistance. Recent progress in green crosslinking strategies and biodegradable adhesive technologies has expanded the potential application range of bio-based adhesives in wood composites, packaging, construction, furniture, automotive components, and selected biomedical uses. Life cycle assessment studies indicate that bio-based adhesives can reduce fossil resource use, toxicity, and greenhouse gas emissions compared with conventional petrochemical systems; however, these benefits strongly depend on feedstock selection, processing route, formulation, energy demand, and end-of-life scenario. Despite substantial progress, challenges related to outdoor durability, water resistance, cost, raw-material variability, and large-scale commercialization remain significant. Overall, development in green chemistry, material engineering, and biomass valorization suggests that bio-based adhesives are promising candidates for next-generation bonding technologies, provided that their performance and sustainability are evaluated for each specific application.

**Keywords:** Bioadhesives, Biodegradable adhesives, Nanotechnology, Petrochemical adhesives, Wood composites

### INTRODUCTION

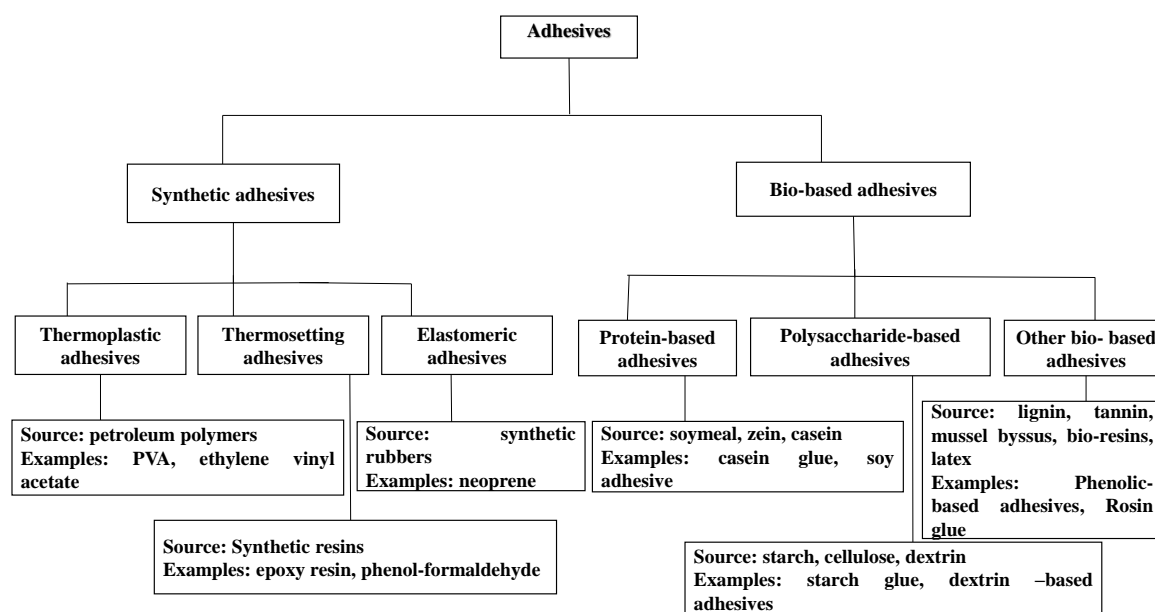
Adhesives are essential polymeric materials used to bond similar or dissimilar substrates in industries such as construction, packaging, electronics, aerospace, automotive engineering, furniture production, and insulation systems (Ebnesajjad, 2011). Their ability to provide strong interfacial adhesion, lightweight assembly, uniform stress distribution, and enhanced structural performance has made them indispensable in modern engineering and industrial applications (Ge & Chen, 2020). In this review, the term bio-based adhesive refers primarily to adhesive systems derived partly or completely from renewable feedstocks, whereas the term bioadhesive may also refer to materials designed to adhere to biological tissues in

biomedical applications. This distinction is important because both fields overlap chemically but differ in performance requirements, test methods, and application environments. Adhesives can broadly be classified into synthetic adhesives and bio-based adhesives. A simplified classification with examples according to source and chemistry is shown in Figure 1 (Kinloch, 2012). Synthetic adhesives are commonly produced from petroleum-derived polymers or monomers, including phenol-formaldehyde, resorcinol-formaldehyde, urea-formaldehyde, epoxy, acrylic, cyanoacrylate, silicone, and polyurethane systems. These materials are widely used because of their high mechanical strength, water resistance, thermal stability, processing reliability, and durability

(Shadlou et al., 2014; Kaybal et al., 2017; Bhandari et al., 2021). However, extensive dependence on petrochemical adhesives raises environmental and health concerns related to volatile organic compounds (VOCs), formaldehyde emissions, limited biodegradability, persistent polymer waste, and depletion of fossil resources (Pizzi, 2016).

Increasing global awareness of sustainability, environmental protection, and green manufacturing has accelerated the development of bio-based adhesives as potential alternatives to conventional petrochemical systems (Xu et al., 2020). Bio-based adhesives can be derived from lignin, tannins, proteins, starch, cellulose, chitosan, vegetable oils, natural rubber, and agricultural residues. These feedstocks can offer advantages such as renewability, low toxicity, biodegradability, and potential carbon-footprint reduction, but they frequently show

limitations in water resistance, long-term durability, shelf life, and processing robustness (Calvez et al., 2024). Recent advances in biopolymer chemistry, nanocomposite formulation, and hybrid crosslinking strategies aim to close these performance gaps by improving mechanical strength, moisture resistance, thermal stability, and durability (Zhang et al., 2023). In parallel, binderless wood-based composite panels (WBCPs) have attracted attention because they rely on self-bonding mechanisms of lignocellulosic materials instead of added synthetic binders (Nitu et al., 2020). The transition from petroleum-based adhesives to bio-based adhesive technologies, therefore, represents a promising pathway toward more sustainable industrial development and a circular bioeconomy, but the suitability of each formulation must be assessed in relation to the specific substrate, processing route, service environment, and end-of-life scenario.

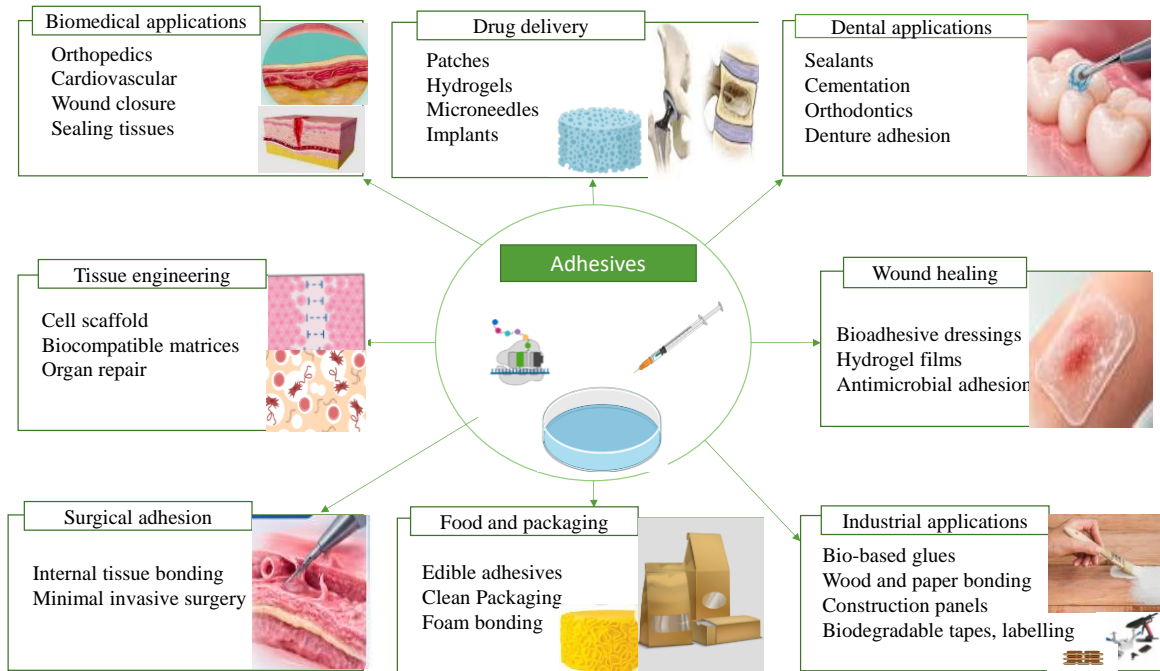


**Figure 1.** General classification-of adhesives based on their sources (Kinloch, 2012)

Bioadhesives and bio-based adhesives contribute to a wide range of sectors, including biomedical applications, drug delivery, tissue engineering, dental applications, food packaging, wood bonding, paper bonding, construction panels, and other industrial uses. Figure 2 illustrates application fields that include wound closure, tissue sealing, drug delivery systems, dental cementation, food-safe packaging, and industrial bonding.

Bioadhesives have become particularly relevant in dental, wound-healing, and surgical applications,

where conventional mechanical fixation methods such as sutures, staples, and wires may damage tissue. In these applications, adhesive hydrogels and related materials can support wound closure and may additionally provide antibacterial or anti-inflammatory functionality (Zhao et al., 2022). At the same time, industrial bio-based adhesives are being developed for wood, paper, packaging, and composite applications, where performance requirements are dominated by bond strength, water resistance, processability, durability, and cost.

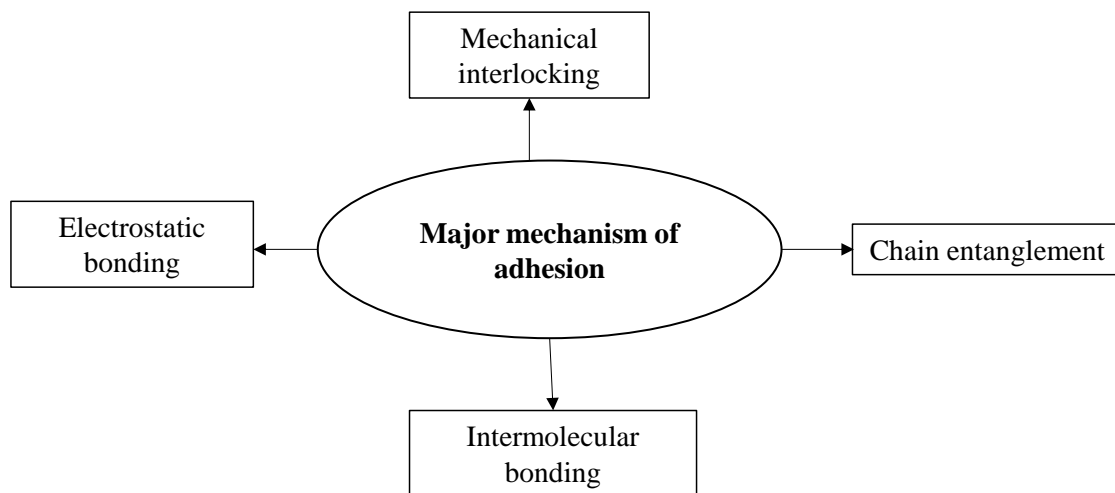


**Figure 2.** Application of adhesives in multiple domains such as pharmaceuticals, drug delivery, dental, tissue engineering, implantation, orthodontics, food packaging, and other industrial purposes for construction (Ge & Chen, 2020; Taboada et al., 2020; Duan et al., 2021)

**Fundamentals of adhesion**

Adhesion is based on the formation of interactions at the interface between the adhesive and substrate. These interactions can include van der Waals forces, hydrogen bonding, electrostatic attraction, covalent bonding, mechanical interlocking, and interdiffusion, depending on the chemistry and morphology of the

materials involved. The efficiency of an adhesive joint is strongly influenced by surface energy, wetting behavior, roughness, porosity, viscosity, curing conditions, and the mechanical properties of both adhesive and substrate (Messler, 2004; Kinloch, 2012). The main mechanisms relevant to adhesive bonding are summarized in Figure 3.



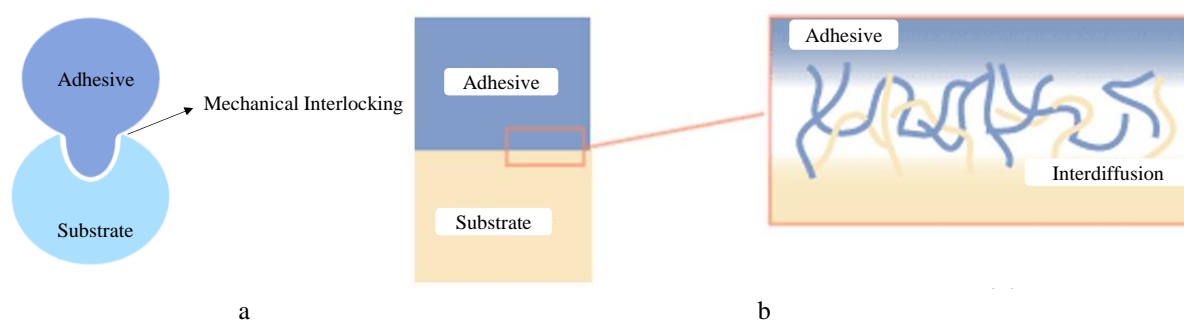
**Figure 3.** Schematic illustration of the adhesion mechanisms involved in adhesive bonding, including mechanical interlocking, chain entanglement, and electrostatic interactions (K., 2023)

### Mechanical interlocking

Mechanical interlocking is an important adhesion mechanism for porous and rough substrates such as wood, paper, textiles, and fiber-based materials. During application and curing, a liquid adhesive can penetrate pores, cracks, lumens, and surface irregularities, thereby forming a physical anchoring effect that improves bond toughness and mechanical stability (Messler, 2004). In lignocellulosic substrates, adhesive penetration into cell lumens and cell walls can support the formation of a durable bond (Pizzi, 2016). The effectiveness of this mechanism depends on surface roughness, porosity, adhesive viscosity, temperature, pressure, and curing time. On very smooth or non-porous surfaces, mechanical interlocking is less effective, whereas excessive roughness can create stress concentrations and reduce joint performance.

### Diffusion theory

Diffusion theory is particularly relevant for polymeric substrates and thermoplastic adhesive systems (Figure 4). In this mechanism, molecular chains from the adhesive and substrate interpenetrate across the interface to form an entangled polymer network, as illustrated in Figure 4(b). The extent of interdiffusion depends on temperature, chain mobility, molecular weight, compatibility, contact time, and curing or solidification conditions (Messler, 2004). This mechanism is most effective when the polymers are chemically compatible and have sufficient segmental mobility. It is less relevant for rigid, highly crosslinked, or strongly heterogeneous substrates such as wood, where adhesion is dominated by wetting, mechanical interlocking, and chemical or secondary interactions (Kinloch, 2012).



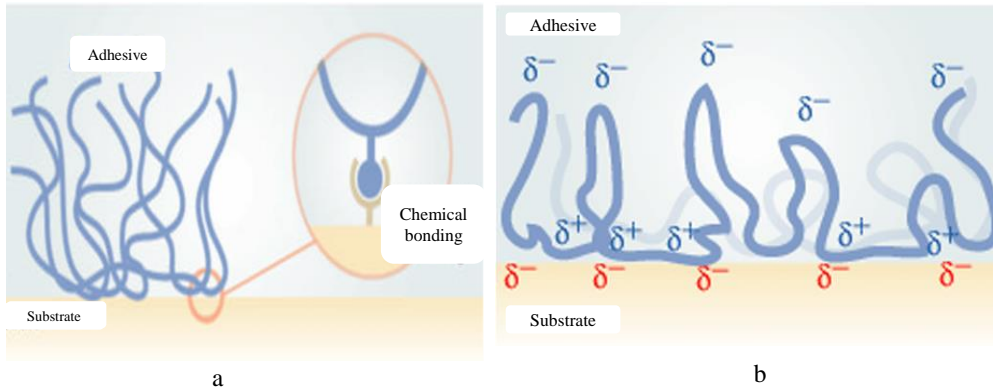
**Figure 4.** Representation of (a) mechanical adhesion, (b) the mechanism of interdiffusion (Donohue, 2003)

### Chemical bonding and intermolecular interaction

Chemical bonding and intermolecular interactions can substantially increase adhesive performance. Covalent, ionic, hydrogen-bonding, and dipole interactions may form between functional groups of the adhesive and reactive sites on the substrate. Natural polymers often contain hydroxyl, carboxyl, amino, phenolic, or thiol groups that can interact with lignocellulosic substrates through hydrogen bonding or, after suitable modification, through covalent crosslinking (Alinejad et al., 2019). These interactions can contribute to three-dimensional network formation, thereby improving bond strength, thermal stability, and water resistance (Pizzi, 2016). However, effective chemical bonding requires compatible functional groups, sufficient wetting, appropriate curing conditions, and stable interfacial chemistry.

### Electrostatic interactions

Electrostatic interactions arise from differences in surface charge or electronic properties between the adhesive and substrate. They can contribute to adhesion through attractive forces at the interface and the formation of an electrical double layer (Fig. 5b) (Kinloch, 2012). In most structural adhesive joints, electrostatic interactions alone are not sufficient to provide high bond strength, but they may support adhesion in polymer-metal, polymer-ceramic, or charged biopolymer systems. Their contribution is often difficult to quantify experimentally because several adhesion mechanisms usually act simultaneously (Messler, 2004).



**Figure 5.** Scheme of (a) Chemical bonding on adhesion (b) Electrostatic double layer (Donohue, 2003)

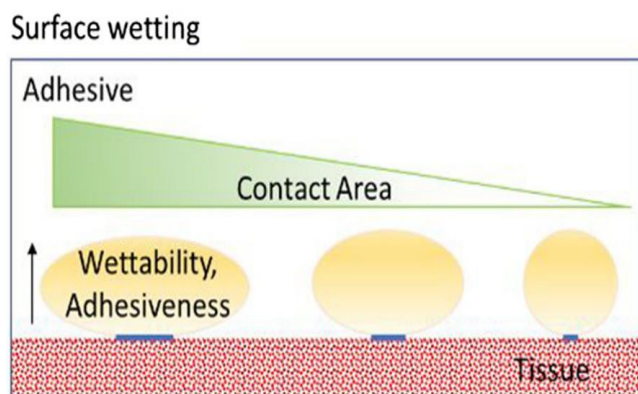
### Surface energy and wetting

Surface energy and wetting are central concepts in adhesive bonding. Good wetting allows the adhesive to spread over the substrate and form intimate molecular contact. Young's equation (equation 1) describes the balance of interfacial energies at the three-phase contact line between solid, liquid, and vapor. A lower contact angle generally indicates better wetting and a larger contact area, which can improve adhesion if the adhesive also has sufficient cohesive strength (Kinloch, 2012). For polar natural polymers, functional groups such as hydroxyl, carboxyl, and amino groups can promote wetting and hydrogen bonding with lignocellulosic substrates. However, good wetting alone does not guarantee durable adhesion; curing, crosslink density, moisture

sensitivity, and interfacial stability must also be considered.

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos \theta \quad \dots (1)$$

In Young's equation,  $\gamma_{SV}$  denotes the solid-vapor surface energy,  $\gamma_{SL}$  the solid-liquid interfacial energy,  $\gamma_{LV}$  the liquid-vapor surface tension, and  $\theta$  the contact angle. Lower values of  $\gamma_{SL}$  and  $\theta$  generally indicate better wetting of the substrate by the adhesive. When the contact angle approaches to zero, the adhesive spreads extensively over the surface, as shown schematically in Figure 6. In practical adhesive systems, optimum bonding requires a balance between wetting, penetration, cohesive strength, curing behavior, and resistance to water or thermal degradation.



**Figure 6.** Mechanism of surface wetting showing a contact angle close to zero (Zhang et al., 2021)

### Classification of bio-based adhesives

Bio-based adhesives can be classified according to their main renewable polymer or feedstock component, including proteins, polysaccharides, lipids, lignin, tannins, and bio-inspired materials

(Eisen et al., 2020). This classification is useful because each feedstock class provides characteristic functional groups, processing behavior, degradation pathways, and performance limitations.

### Natural polymer-based adhesives

Natural polymer-based adhesives are derived from biological macromolecules, including proteins, carbohydrates, and lipids, which offer excellent adhesion properties due to their functional groups that promote bonding (Arias et al., 2021).

#### Protein-based adhesives

Protein-based adhesives use proteins as the primary bonding component. They have been widely studied because proteins contain reactive amino acid side chains capable of hydrogen bonding, ionic interactions, and covalent crosslinking. Examples include soy protein adhesives from soybean meal, which can be modified with crosslinkers to improve water resistance and bond strength (Li et al., 2021); casein adhesives, which are traditionally used in wood and paper bonding (Zhou et al., 2022); gelatin adhesives derived from collagen hydrolysis, which are relevant in pharmaceutical and biomedical contexts because of their biocompatibility (Liu et al., 2022); and albumin-based adhesives from egg white or bovine serum albumin, which have been investigated for tissue-engineering applications (Wijaya et al., 2015).

#### Carbohydrate-based adhesives

Carbohydrate-based adhesives rely on polysaccharides and offer high renewability and biodegradability. Starch adhesives derived from corn, wheat, potato, or cassava are widely used in paper and packaging applications (Zhu et al., 2023). Cellulose-based adhesives and cellulose derivatives can provide improved strength and water resistance after chemical modification (Sun et al., 2022). Chitosan adhesives, obtained from chitin sources such as crustacean shells, contain amino and hydroxyl groups and can show antimicrobial activity, which makes them attractive for medical and packaging applications. Alginate adhesives, sourced from seaweed, can form gels and are therefore relevant for biomedical applications (Zhu et al., 2023).

### Lipid-based adhesives

Lipid-based adhesives include systems derived from plant oils, waxes, and natural resins. Vegetable-oil derivatives, for example, from soybean or castor oil, can be converted into polyols, epoxides, or other reactive intermediates for polyurethane, epoxy, or pressure-sensitive adhesive formulations (Li et al., 2021). Natural waxes and plant resins such as rosin can contribute tack, hydrophobicity, and flexibility in hot-melt and pressure-sensitive adhesive systems (Zhang et al., 2023).

#### Lignin and tannin-based adhesives

Lignin and tannins are abundant phenolic compounds found in plants and trees, often used as bio-based alternatives to synthetic phenol-formaldehyde resins. Lignin-based adhesives are by-products of the paper and bioethanol industries. Lignin adhesives exhibit strong mechanical properties when modified with fillers (Alinejad et al., 2019). Tannin-based adhesives are obtained from tree bark. Tannins have a natural crosslinking affinity. It elevates their use in wood bonding and composites (Pizzi, 2024).

#### Bio-inspired adhesives

Bio-inspired adhesives mimic adhesion strategies found in biological organisms. Mussel-inspired adhesives are based on catechol chemistry and can provide strong wet or underwater adhesion (Lee et al., 2020). Gecko-inspired dry adhesives use micro- and nanoscale structures to exploit van der Waals forces and enable reversible adhesion. Spider-silk-inspired systems aim to combine toughness, elasticity, and biocompatibility through engineered protein structures (Singh et al., 2022). Table 1 summarizes selected biological sources, compounds, bonding mechanisms, and typical applications, along with direct primary renewable feedstock used in adhesive formulation. It differentiates materials directly used as biomass sources from those contained through extraction, chemical conversion, fractionation, or microbial biosynthesis.

**Table 1.** Classification of bio-based adhesives by source

Biological source	Compound	Major bonding mechanism	Direct primary renewable feedstock used in adhesive formulation	Applications	References
<i>Penicillium oxalicum</i>	Anhydrous citric acid	Polycondensation	No	Wood composites	Mahnič et al., 2024
Shrimp and other crustaceans	Chitosan (Carbohydrate)	Hydrogen bonding, ionic interaction, or chemical crosslinking	No	Medicine, wood composites	Luo et al., 2026

<i>Vibrio parahaemolyticus</i>	Exopolysaccharides	Polyaddition	No	Research	Liu & Chen, 2015
Flowering plants	Natural rubber latex	Natural polymer formation	Yes	Wood composites	Perumal et al., 2013
Wood	Lignin (Aromatic polymer)	Phenolic crosslinking, Covalent bonding	No	Wood composites, foams	Kumar et al., 2025
Oleaginous plants	Polyols	Polyurethane curing reaction	Yes	Wood composites, foams	Somani et al., 2003
Wheat, fish, rapeseed cake	Protein	Covalent and Hydrogen Bonding	Yes	Paper	Fahmy et al., 2010
Potatoes	Starch (Carbohydrate)	Hydrogen bonding, ester crosslinking	Yes	Packaging	Admase et al., 2024
Tree bark, cork	Suberin	Polycondensation	No	Wood composites	Isikgo et al., 2015
Flowering plants	Tannin (Polyphenol)	Phenolic crosslinking	Yes	Wood composites	Aristri et al., 2021
Wood	Hemicellulose (Carbohydrate)	Hydrogen bonding, ester crosslinking	No	Wood composites	Isikgor et al., 2015
Vanilla planifolia	Vanillin (Phenol)	Phenolic crosslinking	Yes	Orthodontics	Sini et al., 2014

\* "Yes" indicates direct use of the biomass in the adhesive formulation, "No" denotes the compound used as secondary intermediates or processed bio- derived alternatives.

Synthetic adhesives are generally prepared from non-renewable petrochemical monomers or polymers such as phenol, urea, melamine, formaldehyde, epoxy resins, acrylics, silicones, polyurethanes, and related systems. They are often cost-effective and provide high mechanical strength, thermal stability, water

resistance, and processing reliability, as summarized in Table 2. However, fossil-derived adhesive systems may contribute to VOC emissions, formaldehyde exposure, persistent waste, and environmental burdens, which motivates the search for renewable and lower-emission alternatives (Antov et al., 2020).

**Table 2.** Overview of synthetic adhesives and their application

Adhesive type	Key characteristics	Common applications
Epoxy	Strong adhesion, heat resistance, durable under harsh conditions, easy to use, cost-effective, and cures at relatively low temperatures (for 2K systems).	Suitable for bonding metals, ceramics, and polymers (Caldas et al., 2019).
Acrylics	Offers design flexibility, high strength, rapid curing, and can bond to surfaces with minimal preparation.	Commonly used for cloth, plastics, and metals (Aronovich & Boinovitch, 2021).
Polyurethanes	Flexible even at low temperatures, impact and fatigue resistant, ideal for bonding dissimilar materials.	Works well with plastics, metals, and rubber (Abu Bakar et al., 2024).
Cyanoacrylates (Superglues)	Rapid adhesion to plastic and rubber but has poor resistance to moisture and high temperatures.	Bonds a wide variety of materials (Ebnesajjad, 2011).
Anaerobic Adhesives	Cures without exposure to light, heat, or oxygen, often used for fastening and sealing cylindrical components.	Primarily used for metals (Sineokov et al., 2008).
Silicones	Highly flexible, excellent for sealing, withstands extreme temperatures, long curing time (for 1K systems), but low strength.	Used with metals, glass, paper, plastics, and rubber (Han et al., 2022).

Phenolics	Maintains strength for short durations, offers limited thermal shock resistance, and is cost-effective.	Applied to metals and wood (Mardani et al., 2026).
Polyimides	High thermal stability but influenced by various factors, challenging to process, and relatively expensive.	Used with cloth and plastics (Hergenrother, 1990).
Bismaleimides	Rigid with low peel strength.	Suitable for bonding metals, glass, ceramics, and plastics (Kajiyama 2002).
Amino Resins (e.g., Urea-Formaldehyde)	Strong, rigid, cost-efficient, and fast-curing.	Commonly used in wood applications (Bhandari et al., 2019).

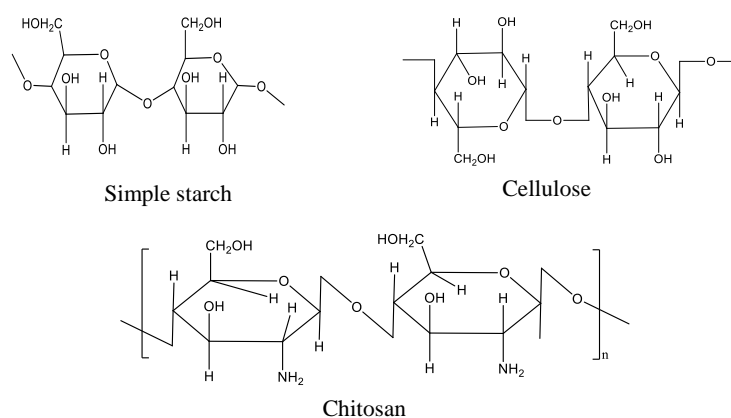
### Chemical structure of bio-based adhesive

The performance of bio-based adhesives depends strongly on molecular structure, functional-group density, molecular weight, crosslinking chemistry, morphology, and interactions with the substrate. Hydroxyl, carboxyl, amino, phenolic, and thiol groups can promote wetting, hydrogen bonding, ionic interactions, and covalent crosslinking. Therefore, understanding chemical structure is essential for

tailoring adhesion strength, elasticity, thermal stability, water resistance, and degradation behavior for specific applications.

### Polysaccharide-based adhesives

Starch, cellulose, and chitosan are polysaccharides rich in hydroxyl groups and are therefore widely investigated as bio-based adhesive components. Their hydroxyl groups facilitate hydrogen bonding with polar substrates.



**Figure 7.** Chemical structures of different polysaccharides (Takada & Kadokawa, 2015)

Starch consists mainly of linear amylose and branched amylopectin. Amylose can contribute strength through ordered or crystalline domains, whereas amylopectin can influence flexibility, viscosity, and film-forming behavior (Saha et al., 2020). Modified cellulose derivatives, such as carboxymethyl cellulose and hydroxypropyl cellulose, can improve solubility, processability, and hydration behavior. Chitosan contains both amino and hydroxyl groups, which can support hydrogen bonding, ionic interactions, and chemical crosslinking, thereby improving cohesion

and water resistance (Hong et al., 2025). Figure 7 shows representative structures of starch, cellulose, and chitosan.

### Protein-based adhesives

Proteins such as soy protein, casein, and gelatin contain peptide backbones and reactive side groups, including carboxyl, amino, hydroxyl, and thiol groups. These groups enable hydrogen bonding, ionic interactions, and covalent crosslinking with suitable curing agents.

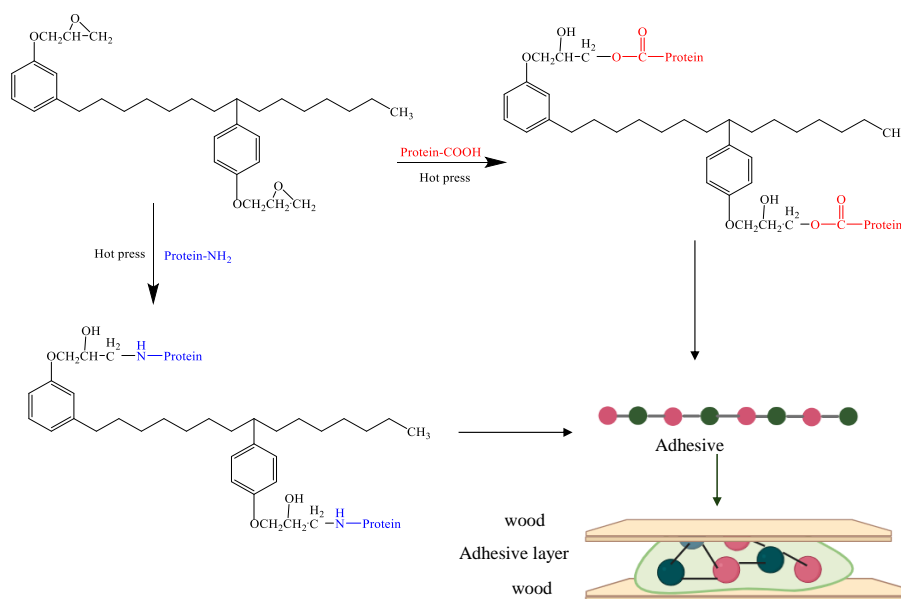


Figure 8. Simple reaction of soybean protein-based adhesive (Zhu et al., 2022)

In soy protein adhesives, water resistance and cohesive strength are often improved by denaturation, crosslinking, or reaction with aldehydes, epoxides, polycarboxylic acids, or other multifunctional compounds, frequently combined with hot pressing as shown in Figure 8. Casein binders rely on a combination of hydrogen bonding, ionic interactions, and hydrophobic interactions; calcium salts and other additives can improve wet adhesion and network formation (Zhang et al., 2025).

### Biobased polyesters and polyurethanes

Bio-based polyurethanes have attracted considerable attention in adhesive applications because urethane

linkages can provide strong hydrogen bonding, toughness, flexibility, and adhesion to both polar and selected non-polar substrates (Alinejad et al., 2019). Renewable polyols can be obtained from vegetable oils, lignin, lactic acid, itaconic acid, or other biomass-derived intermediates. These polyols can react with diisocyanates to form partially or fully bio-based polyurethane adhesives, depending on the origin of both the polyol and isocyanate components. Figure 9 illustrates the preparation of a polyester polyurethane from modified castor-oil-based polyol and partially bio-based hexamethylene diisocyanate (PBHDI).

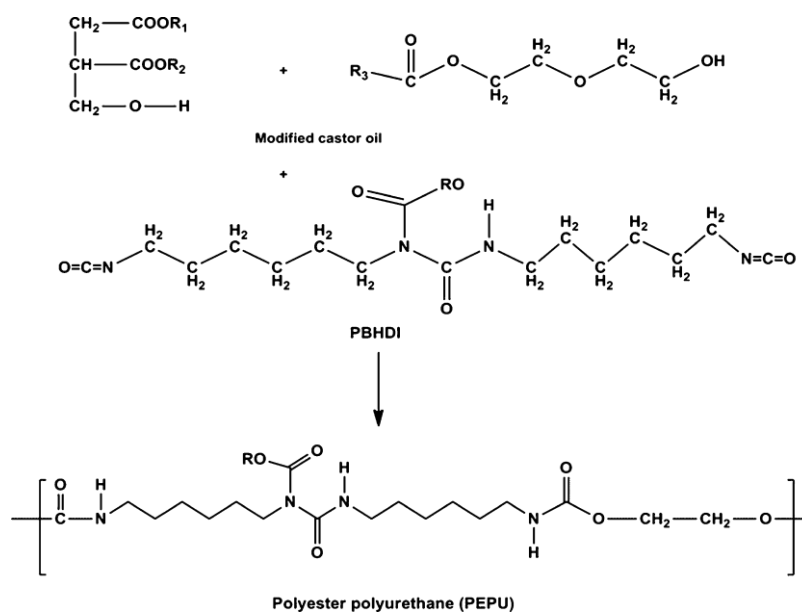
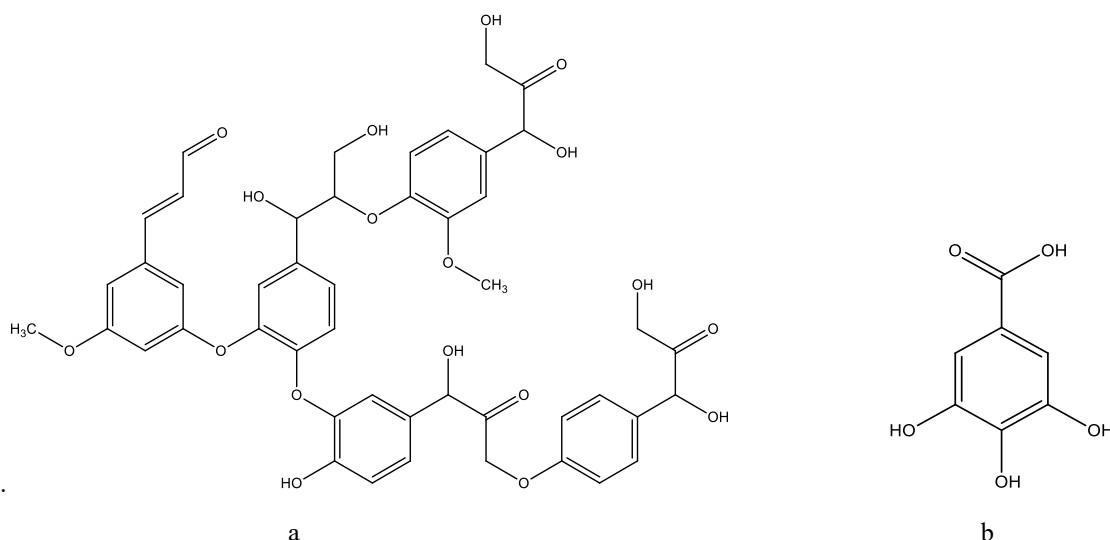


Figure 9. Preparation of polyester polyurethane from modified castor oil (Sahoo et al., 2018)

### Lignin and tannin-based adhesives

Lignin and tannins are aromatic polyphenolic compounds that are particularly relevant for wood adhesives. Lignin contains phenolic hydroxyl groups, aliphatic hydroxyl groups, methoxy groups, and aromatic structures that can interact with lignocellulosic substrates and participate in crosslinking reactions after chemical modification



**Figure 10.** Chemical structure of (a) lignin, (b) tannin (Alinejad et al., 2019)

## CHALLENGES AND LIMITATIONS

### Low water resistance and durability

Many bio-based adhesives, particularly starch- and protein-based systems, exhibit limited water resistance and long-term durability because of their hydrophilic functional groups. Moisture absorption can lead to swelling, plasticization, hydrolysis, microbial degradation, or loss of cohesive strength. Chemical crosslinking, hydrophobic modification, blending with more water-resistant polymers, and incorporation of nanofillers are therefore widely used to improve wet strength and dimensional stability.

### Scaling up production while maintaining cost-effectiveness

Although bio-based adhesives offer sustainability benefits, large-scale production faces economic and technological barriers. Feedstock availability, seasonal and regional variability, purification requirements, processing energy, formulation complexity, and quality control can strongly influence cost. In addition, renewable feedstocks may compete

(Figure 10). Tannins contain multiple phenolic hydroxyl groups and can react with aldehydes, glyoxal, furfuryl alcohol, or other crosslinkers to form phenolic networks. Because of their aromatic structure, lignin- and tannin-based adhesives can offer stiffness, thermal stability, and partial hydrophobicity, but their reactivity, solubility, and batch-to-batch variability must be carefully controlled (Kumar et al., 2025)

with food, feed, or other material uses. For commercial adoption, bio-based adhesives must therefore meet performance requirements while remaining compatible with industrial processing and economically competitive with established synthetic systems.

### Compatibility with existing industrial applications

Industries using synthetic adhesives have optimized manufacturing processes, application equipment, curing conditions, and quality-control procedures for conventional formulations. Transitioning to bio-based alternatives requires compatibility with existing processing windows, substrates, application methods, pressing cycles, storage conditions, and regulatory requirements. Reformulation may also require new testing protocols to demonstrate bond strength, water resistance, durability, emissions behavior, and long-term reliability.

### Need for further research in bio-based monomers and polymerization techniques

Despite advancements, bio-based adhesives require extensive research in monomer selection and

polymerization techniques to enhance their performance. Innovative bio-based monomers with improved adhesion, mechanical strength, and environmental stability are essential for meeting industrial demands. Enzymatic polymerization, biocatalytic synthesis, and hybrid formulations have shown promise in improving bio-adhesive properties. Additionally, bio-inspired strategies, such as mussel-inspired catechol chemistry, offer novel approaches to enhance adhesion strength and water resistance (Yu et al., 2021).

### RECENT ADVANCES IN BIO-BASED ADHESIVES

Ongoing research in bio-based adhesives focuses on improving adhesion strength, water resistance, and durability through various chemical, enzymatic, and nanotechnological modifications. The development of bio-based polyurethane and epoxy adhesives, as well as biodegradable and compostable formulations, has further expanded the potential applications of these adhesives, which are illustrated below (Arias et al., 2021).

#### Modification techniques for enhancing adhesion strength and water resistance

Bio-based adhesives often show limited water resistance, variable cohesive strength, or insufficient durability compared with established petrochemical systems. These drawbacks can be mitigated through chemical modification, enzymatic treatment, hybrid

formulation, nanofiller reinforcement, and optimized curing strategies.

Chemical modification is one of the most effective approaches for improving the performance of bio-based adhesives. Feedstocks such as lignin, starch, tannin, soy protein, cellulose, and vegetable oils contain functional groups that can be esterified, etherified, epoxidized, oxidized, or crosslinked. For example, crosslinking with glutaraldehyde or isocyanates enhances the water resistance of soy protein adhesives, as shown in Figure 11. In the same way, the aid of tannin into lignin-based adhesives yields effective bonding stability (Watcharakitti et al., 2022). Such modifications can increase cohesive strength, reduce water sensitivity, improve thermal stability, and tailor viscosity and curing behavior.

Recent studies have demonstrated that incorporating bio-based crosslinkers, such as tannic acid, citric acid, furfural, and vanillin, enhances the thermal stability and moisture resistance of adhesives while reducing dependence on petroleum-derived chemicals. For example, glyoxal-modified soy protein adhesives showed improved wet shear strength as well as reduced formaldehyde emission compared to traditional urea formaldehyde systems (Bhandari et al., 2019). Moreover, polyurethane adhesives based on renewable polyols derived from castor oil, cardanol, and lignin exhibited excellent flexibility and good interfacial bonding performance (Zhen et al., 2024).

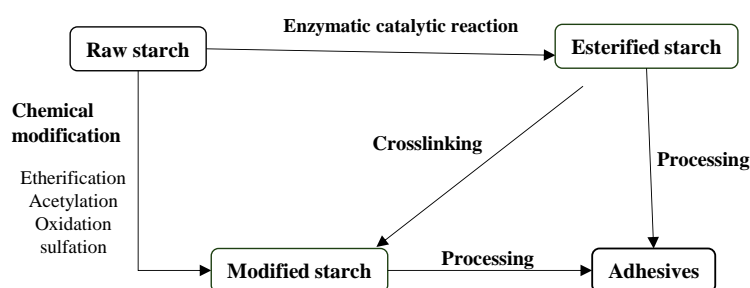
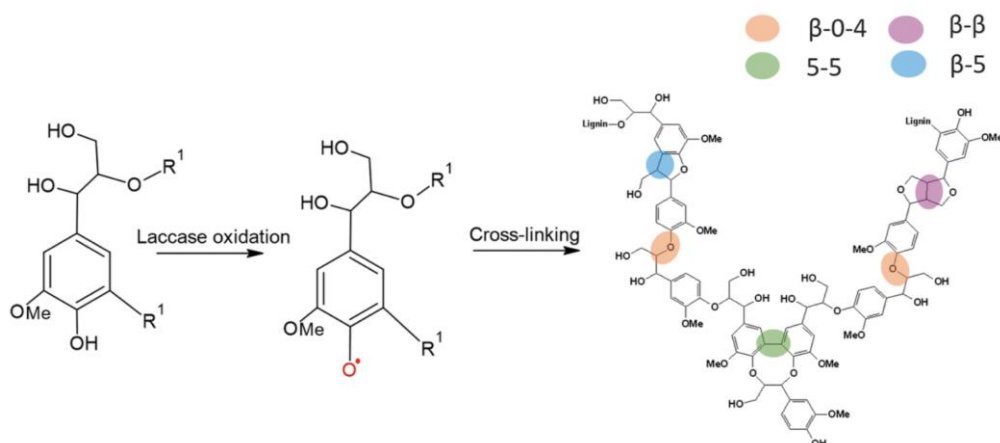


Figure 11. Chemical modification of starch-based adhesive by crosslinking agents (Watcharakitti et al., 2022)

Enzymatic modification can provide milder and potentially more selective routes for modifying lignin, tannins, polysaccharides, and proteins. Laccase, peroxidase, transglutaminase, and related enzymes can promote oxidative coupling or crosslinking reactions under relatively mild conditions (Fig. 12).

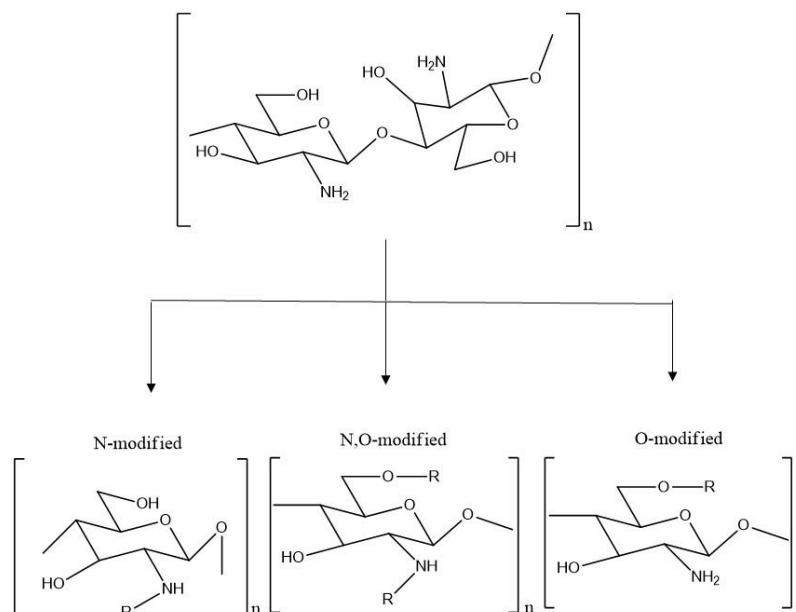
These approaches may reduce the need for toxic aldehyde-based curing agents and can lower VOC emissions, although enzyme cost, reaction time, process control, and scalability remain important challenges.



**Figure 12.** Phenolic groups oxidation by laccase-mediated reaction and highlighting the main linkages occurring during polymerization:  $\beta$ -O-4 ( $\beta$ -aryl ether),  $\beta$ - $\beta$  (resinol),  $\beta$ -5 (phenylcoumaran), and C5-C5 (Cunha et al., 2025)

Hybrid formulations combine bio-based polymers with limited amounts of synthetic resins, reactive crosslinkers, or reinforcing phases. The aim is to retain the sustainability advantages of renewable feedstocks while improving bond strength, cohesion, water resistance, and processing reliability. However, the environmental benefit of hybrid systems must be

assessed carefully, because the addition of synthetic components may reduce biodegradability or complicate end-of-life management. Figure 13 shows that the chemical alteration of chitosan using an inorganic crosslinker creates a hybrid formulation for improved adhesive activity.



**Figure 13.** Chemical structure, reactive functional groups, and chemical modification of chitosan for synthesis of a hybrid bio-based adhesive (Calvez et al., 2024)

### Nanotechnology in bio-based adhesives

Nanotechnology has gained increasing attention in bio-based adhesive research. Traditional starch-, protein-, and lignin-based adhesives may show limited thermal resistance, poor dimensional stability, or low water resistance. Nanofillers such as cellulose

nanocrystals, nanocellulose fibrils, nanoclays, lignin nanoparticles, chitosan nanoparticles, graphene derivatives, or mineral nanoparticles can reinforce the adhesive network, improve barrier properties, and enhance stress transfer at the interface when they are well dispersed and compatible with the matrix.

### **Nanocellulose**

The addition of cellulose nanocrystals (CNCs) reinforces protein- and starch-based adhesives, leading to improved bond strength and moisture resistance. This enables the formation of more compact and interconnected structures along with reduced microvoid formation within the adhesive film (Zhou et al., 2022).

### **Graphene oxide**

The graphene oxide in soy protein adhesives has been shown to increase their mechanical activity. The oxygen-containing functional group creates a strong surface reaction, like an electrostatic interaction with protein chains. It limits the polymer chain mobility as it increases stiffness and overall structural integrity. Moreover, graphene oxide has a two-dimensional layered structure, which helps in improving resistance to environmental degradation under moisture and thermal stress (Zhang et al., 2023).

### **Bio-based nanoparticles**

Biopolymer-based nanoparticles, such as chitosan and lignin nanoparticles, have been explored for their ability to improve adhesion strength while maintaining biodegradability. They show increased network formation, surface bonding, and decreased porosity (Sun et al., 2022).

### **Development of bio-based polyurethane and epoxy adhesives**

Polyurethane and epoxy adhesives derived from renewable sources have gained interest due to their high mechanical strength and resistance to harsh environments.

#### **Bio-based polyurethane adhesives**

Polyurethane adhesives synthesized from vegetable oils and lignin-based polyols have been developed as alternatives to petroleum-based polyurethane adhesives (Ferrandez-Villena et al., 2020). These bio-based formulations exhibit strong adhesion and flexibility while maintaining biodegradability.

#### **Bio-based epoxy adhesives**

Epoxy adhesives derived from bio-based precursors, such as cardanol and epoxidized plant oils, show excellent mechanical and thermal properties suitable for construction and automotive applications (Wang et al., 2019)

### **Emerging Research on Biodegradable and Compostable Adhesives**

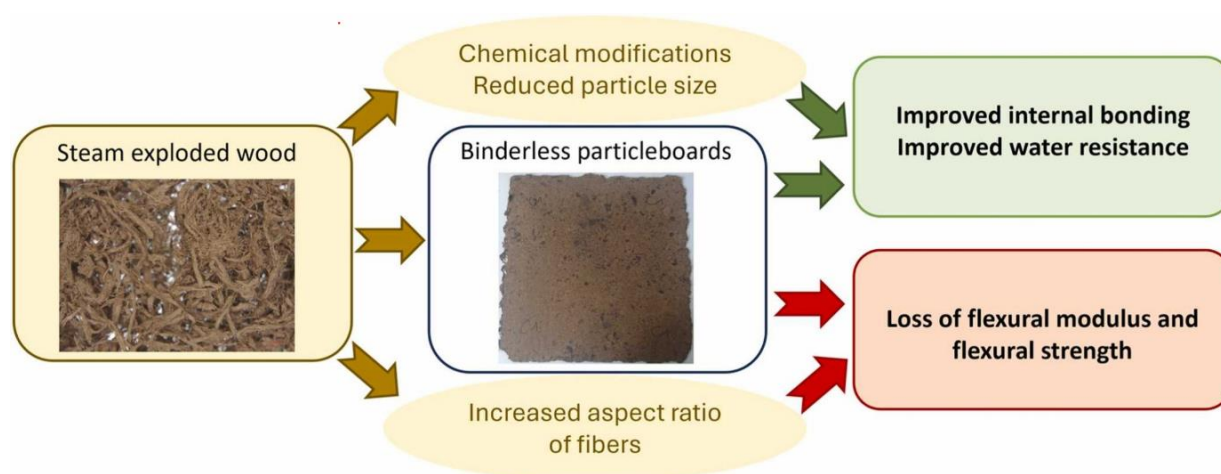
Fully biodegradable or compostable adhesives are being developed to address adhesive-related waste,

especially in packaging, paper, hygiene, agriculture, and selected biomedical applications. However, biodegradability must be evaluated under defined conditions, such as industrial composting, home composting, soil, marine, or physiological environments. A general claim of biodegradability is insufficient unless supported by standardized testing and a clearly defined end-of-life scenario.

### **Binderless wood-based composite panels (WBCPs)**

Binderless panels are produced without adhesives by activating the chemical components of wood through heat and pressure. During processing, lignocellulosic materials undergo degradation through steam explosion, enzymatic modifications, and fungal treatments, generating monomers with free radicals that promote self-bonding to optimize adhesion (Ferrandez-Villena et al., 2020). The breakdown of lignin and hemicelluloses releases acetone, organic acids, and furfural acids, which polymerize and act as natural binding agents (Nitu et al., 2020).

To enable effective bonding, wood polymers must be plasticized above their glass transition temperature. Acidic compounds from hemicellulose degradation catalyze cellulose and hemicellulose breakdown, leading to recondensation reactions that form natural resins or bonds with lignin. As the material cools, plasticized lignin solidifies around cellulose and hemicellulose. It notably affects the final mechanical properties of the panel (Kaybal et al., 2017). The self-bonding method in binderless panels is affected by several factors. It involves temperature, pressure, pressing time, and particle size. The main reactions display as hemicellulose hydrolysis, the release of reactive compounds that enhance bonding. Moreover, it can be achieved by lignin softening, which facilitates the adhesion of fibers during hot pressing (Kaybal et al., 2017). Figure 14 explains the formation of binderless particle boards from the pretreatment of wood through steam explosion. It illustrates that the woody biomass is treated with high-pressure steam by rapid decompression to disrupt the lignocellulosic bond. Audibert et al. (2025) also reported that such a process exposes the lignin and creates natural adhesion. Such samples are then hot pressed without any synthetic adhesive to form particle board. Self-bonding in WBCPs relies on the above parameters. Lately, researchers get attentive towards pre-treatment methods to enhance the bonding of fiber, which is explained below (Chen et al., 2024).



**Figure 14.** Schematic representation of binderless particle boards from steam-exploded woody biomass, where steam eruption improves lignin homogenization and self-adhesion behavior of the fibers (Audibert et al., 2025)

### Mechanical pre-treatment

Mechanical pretreatment can enhance fiber bonding by increasing accessible surface area, opening fiber structures, and improving the availability of lignin and hemicellulose at the interface. Steam explosion can improve self-bonding by disrupting cell-wall structures, exposing fibrils, and redistributing lignin, which may contribute to water resistance and cohesive strength (Ferrandez-Villena et al., 2020).

### Chemical pre-treatment

Chemical pretreatment can be acidic or alkaline. Acid treatment can hydrolyze lignocellulosic components and increase the availability of reactive groups, but excessive degradation may reduce mechanical performance. Alkaline pretreatment can remove or redistribute lignin and hemicellulose and increase fiber surface roughness and reactivity. The choice of pretreatment must balance improved bonding with preservation of fiber integrity and process sustainability (Kumar et al., 2025).

### Biological pre-treatment

Biological pretreatments using enzymes or fungi, especially white-rot fungi, can selectively modify lignin and hemicellulose and thereby improve bonding potential. Mycelium-based biocomposites use fungal growth to create interwoven networks that bind lignocellulosic particles. Processing parameters such as time, humidity, temperature, species selection, and sterilization strongly influence final properties and reproducibility (Chen et al., 2024).

### PERFORMANCE EVALUATION OF BIO-BASED ADHESIVES

Bio-based adhesives are evaluated using mechanical, physical, thermal, chemical, and durability-related test methods. These evaluations provide information on adhesion strength, cohesive strength, water resistance, thermal stability, aging behaviour, and interfacial interactions, as summarized in Figure 15.

#### Mechanical properties

Shear strength describes the maximum shear stress that an adhesive joint can resist when loaded parallel to the bonded interface. It is commonly used to assess wood, composite, metal, and polymer bonding performance. Bio-based adhesives reinforced with nanomaterials or chemically crosslinked networks can show improved shear strength, but results depend strongly on substrate, surface preparation, adhesive spread rate, curing conditions, and test standard (Chen et al., 2024).

Tensile strength describes the maximum tensile stress that an adhesive film or bonded joint can withstand under tensile loading. For adhesive films, dumbbell-shaped specimens may be tested until failure to evaluate cohesive strength. For bonded joints, tensile or pull-off tests can be used to assess adhesion perpendicular to the interface. A clear distinction between adhesive-film testing and bonded-joint testing is necessary when comparing results.

#### Bond durability

It examines the long-term performance of the adhesive under humidity, temperature, or water immersion. The chemical changes in the functional group are evaluated through FTIR (Sun et al., 2022).

## Physical properties

Water resistance measures the ability of an adhesive or bonded joint to retain strength and dimensional stability under moisture exposure or water immersion. Depending on the application, samples may be

subjected to soaking, boiling-water tests, humidity aging, cyclic wet-dry exposure, or standardized wood-panel tests. Microscopy, FTIR, SEM, swelling measurements, and residual bond-strength testing can be used to evaluate degradation mechanisms (Zhu et al., 2023).

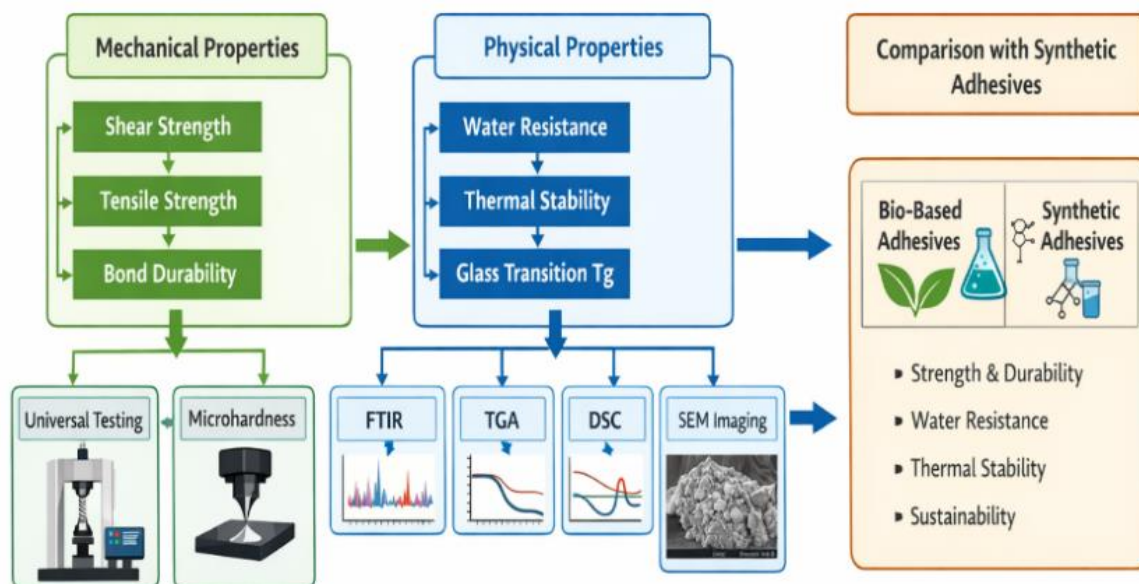


Figure 15. Performance evaluation of biobased adhesives (Dunky et al., 2023; Zhao et al., 2022; Chen et al., 2024)

Thermal stability can be evaluated using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), and heat-aging tests. TGA provides information on mass loss and decomposition stages, DSC can reveal transitions such as glass transition, melting, crystallization, or curing reactions, and DMA can assess viscoelastic behaviour and mechanical stability as a function of temperature.

## COMPARATIVE ANALYSIS: BIO-BASED VS. SYNTHETIC ADHESIVES

Bio-based adhesives offer sustainable alternatives to conventional synthetic adhesives, but their performance must be critically compared across several parameters to assess their viability in industrial applications.

### Mechanical properties (bond strength, durability, flexibility, and resistance to heat/moisture)

Synthetic adhesives, particularly epoxy and polyurethane-based formulations, are known for their superior bond strength, flexibility, and resistance to heat and moisture (Pizzi, 2016). However, recent advancements in bio-based adhesives, such as lignin-

phenol blends and nanocellulose-reinforced adhesives, have significantly improved their mechanical durability and resistance to environmental factors (Heinrich, 2019).

### Biodegradability and environmental impact

Bio-based adhesives can have lower environmental footprints when derived from renewable resources, produced efficiently, and designed for suitable end-of-life pathways. However, environmental performance is not guaranteed by bio-based origin alone. Agricultural inputs, land use, feedstock purification, chemical modification, drying energy, crosslinker selection, durability, and disposal route can strongly influence the overall life cycle impact. Therefore, LCA results should be interpreted on a formulation- and application-specific basis.

### Cost and scalability challenges

Despite their environmental benefits, bio-based adhesives often face challenges in cost-effectiveness and large-scale production. The processing and chemical modification of natural polymers can increase manufacturing costs, making them less competitive compared to synthetic adhesives (Tout,

2000). However, ongoing advancements in feedstock processing and bio-refinery technologies are helping to bridge this cost gap (Taboada et al., 2020).

**Regulatory and safety considerations**

The use of bio-based adhesives aligns with stringent environmental and safety regulations, particularly those restricting hazardous chemicals like formaldehyde in synthetic adhesives. Industries are increasingly adopting bio-based formulations to comply with green building standards and sustainable product certifications (Audibert et al., 2025).

**FUTURE PERSPECTIVES AND INNOVATIONS**

Green chemistry is driving innovation in bio-based adhesives through enzymatic polymerization, biocatalytic synthesis, solvent-free processing, formaldehyde-free crosslinking, and renewable monomer development. These approaches can reduce hazardous emissions and fossil-resource use while improving application-specific performance. Future

innovations should combine high bond strength, moisture resistance, scalable processing, low emissions, and credible end-of-life concepts.

**LIFE CYCLE ANALYSIS AND ENVIRONMENTAL IMPACTS**

Life cycle assessment (LCA) evaluates the environmental impacts of adhesives from raw material sourcing through production, use, and end-of-life. Several studies indicate that bio-based adhesives can reduce global warming potential, fossil-resource use, and toxicity compared with petrochemical adhesives, but the magnitude of improvement depends strongly on the feedstock, system boundary, allocation method, energy mix, adhesive performance, and durability, summarized in Table 3. Therefore, bio-based adhesives should not be described as automatically superior; instead, each adhesive system should be evaluated using a defined functional unit, such as bonding performance per square meter of panel or per bonded component (Zazo et al., 2025).

**Table 3.** Overall environmental performance of petro and bio-based adhesive (McDevitt & Grigsby, 2014)

Adhesive type	Relative CO <sub>2</sub> emissions/reduction potential	VOC emission	Sustainability
PF/UF synthetic adhesive	High emissions / low reduction potential	High	Non-renewable
Soy-based adhesive	20–30% lower	Low	Renewable
Lignin-based adhesive	Potentially 15-35% lower, formulation-dependent	Very low	Biodegradable
Tannin adhesive	Moderate reduction potential, formulation-dependent	Low	Renewable

**CONCLUSION**

In conclusion, bio-based adhesives have gained significant attention as potential alternatives to petroleum-based adhesives because they can combine renewability, reduced fossil-resource use, lower toxicity, and improved end-of-life options. Recent advances in chemical modification, enzymatic crosslinking, nanofiller reinforcement, bio-based polyurethane and epoxy chemistry, and binderless lignocellulosic composites have improved adhesion strength, water resistance, thermal stability, and durability. Applications include wood composites, paper and packaging, construction panels, furniture, selected automotive components, and biomedical systems.

Nevertheless, production cost, large-scale commercialization, raw-material variability, water

resistance, outdoor durability, long-term aging, and regulatory compliance remain major barriers. Future research should focus on application-specific performance, standardized testing, scalable processing, formaldehyde-free and low-VOC chemistry, robust LCA data, and clear end-of-life concepts. Bio-based adhesives should be positioned not as universal replacements for petrochemical adhesives, but as targeted solutions for applications where sustainability, performance, cost, and durability can be balanced.

**ACKNOWLEDGMENTS**

Authors would like to thank the Research Center for Applied Science and Technology (RECAST), Tribhuvan University, Kathmandu, Nepal for its inspiration and motivation to write this review paper.

## AUTHORS CONTRIBUTION

Conceptualization: NLB, KB, SGC, SS; Methodology: KB, JNB, SS; Validation: KB, JNB, SS; Investigation: NLB, SS; Data analysis: NLB, SS; Writing-original draft: KB, NLB, SGC; Writing-review & editing: MN, RL; Supervision: NLB, JB; Funding acquisition: NLB, KB

## FUNDING

Ministry of Science, Technology, and Innovation (MoSTI), Government of Nepal (Fisca year 2025-2026)

University Grants Commission (UGC) Nepal (PhD-81/82-S&T-09)

## ORCIDs

Kabita Bist:

<https://orcid.org/0009-0005-9209-3199>

Sirisha G.C.:

<https://orcid.org/0009-0005-4622-2033>

Jaga Nath Bashyal:

<https://orcid.org/0009-0002-1152-5905>

Sumita Subedi:

<https://orcid.org/0009-0002-1089-918X>

Ralf Lach:

<https://orcid.org/0000-0003-0590-1468>

Michael Nase:

<https://orcid.org/0000-0002-8017-4849>

Jagadeesh Bhattarai:

<https://orcid.org/0000-0003-0058-079X>

Netra Lal Bhandari:

<https://orcid.org/0000-0002-4534-374X>

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

## ETHICAL STATEMENT

There are no ethical issues in the manuscript.

## DATA AVAILABILITY STATEMENT

Not applicable. All the data and information have been taken from open-access journals.

## SUPPLEMENTARY INFORMATION

None

## REFERENCES

Abu Bakar, F. A., Abd Wahab, M. I., Mohd Daril, M. A., & Abdul Aziz, N. E. S. (2024). Analysis of adhesive wood bond strength using Taguchi methods technique. *Pakistan Journal of Life & Social Sciences*, 22(2), 6036.

<https://doi.org/10.57239/PJLSS-2024-22.2.00451>

Admase, A. T., Fanta, S. W., & Mersha, D. A. (2024). Development and characterization of sustainable biodegradable wood adhesive using starch as the main ingredient. *Journal of the Indian Academy of Wood Science*, 21(2), 332–344.

<https://doi.org/10.1007/s13196-024-00352-3>

Alaneme, K. K., Anaele, J. U., Oke, T. M., Kareem, S. A., Adediran, M., Ajibuwa, O. A., & Anabaranze, Y. O. (2023). Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Alexandria Engineering Journal*, 83, 234–250.

<https://doi.org/10.1016/j.aej.2023.10.012>

Alinejad, M., Henry, C., Nikafshar, S., Gondaliya, A., Bagheri, S., Chen, N., Singh, S. K., Hodge, D. B., & Nejad, M. (2019). Lignin-based polyurethanes: opportunities for bio-based foams, elastomers, coatings and adhesives. *Polymers*, 11(7), 1202.

<https://doi.org/10.3390/polym11071202>

Antov, P., Savov, V., & Neykov, N. (2020). Sustainable bio-based adhesives for eco-friendly wood composites a review. *Wood research*, 65.

Arias, A., González-Rodríguez, S., Barros, M., Salvador, R., Francisco, A., Piekarski, C., & Moreira, M. (2021). Recent developments in bio-based adhesives from renewable natural resources. *Journal of Cleaner Production*, 314, 127892.

<https://doi.org/10.1016/j.jclepro.2021.127892>

Aristri, M. A., Lubis, M. A. R., Iswanto, A. H., Fatriasari, W., Sari, R. K., Antov, P., Gajtanska, M., Papadopoulos, A. N., & Pizzi, A. (2021). Bio-based polyurethane resins derived from tannin: Source, synthesis, characterisation, and application. *Forests*, 12(11), 1516.

<https://doi.org/10.3390/f12111516>

Aronovich, D. a., & Boinovich, L. b. (2021). Structural Acrylic Adhesives: A Critical Review. In *Progress in Adhesion and Adhesives* (pp. 651–708). John Wiley & Sons, Ltd.

<https://doi.org/10.1002/9781119846703.ch15>

Audibert, E., Ducceschi, L., Quintero, A., Martel, F., Paës, G., & Rémond, C. (2025). Binderless particleboards from steam-exploded woody biomass: Chemical and morphological properties relate to their mechanical and physical behavior. *Industrial Crops and Products*, 229, 120983.

<https://doi.org/10.1016/j.indcrop.2025.120983>

Bhandari, N. L., Bhattarai, S., Bhandari, G., Subedi, S., & Dhakal, K. N. (2021). A review on current practices of plastic waste management and future

- prospects. *Journal of the Institute of Science and Technology*, 2026(1), 107-118.  
<https://doi.org/10.3126/jist.v26i1.37837>
- Bhandari, N. L., Dhungana, B. R., Lach, R., Henning, S., & Adhikari, R. (2019). Synthesis and characterization of urea-formaldehyde eco-friendly composite based on natural fibers. *Journal of Institute of Science and Technology*, 24(1), 19-25.  
<http://doi.org/10.3126/jist.v24i1.24623>
- Caldas, I. P., Alves, G. G., Barbosa, I. B., Scelza, P., de Noronha, F., & Scelza, M. Z. (2019). In vitro cytotoxicity of dental adhesives: A systematic review. *Dental Materials*, 35(2), 195–205.  
<https://doi.org/10.1016/j.dental.2018.11.028>
- Calvez, I., Garcia, R., Koubaa, A., Landry, V., & Cloutier, A. (2024). Recent advances in bio-based adhesives and formaldehyde-free technologies for wood-based panel manufacturing. *Current Forestry Reports*, 10(5), 386–400.  
<https://doi.org/10.1007/s40725-024-00227-3>
- Chen, Y., Zhang, Y., Cao, Y., Guo, D., Li, G., Qing, Y., & Wu, Y. (2024). High-performance self-bonding bio-composites from wood fibers. *Industrial Crops and Products*, 209, 117944.  
<https://doi.org/10.1016/j.indcrop.2023.117944>
- Cunha, A. E. P., Rencoret, J., del Río, J. C., & Simões, R. M. S. (2025). Laccase-induced lignin cross-linking and the potential for cellulose-based composite reinforcement. *Industrial Crops and Products*, 226, 120610.  
<https://doi.org/10.1016/j.indcrop.2025.120610>
- Donohue, M. D. (2003). Supercritical fluid spray application process for adhesives and primers. <https://apps.dtic.mil/sti/html/tr/ADA483397/>
- Duan, W., Bian, X., & Bu, Y. (2021). Applications of bioadhesives: A mini review. *Frontiers in Bioengineering and Biotechnology*, 9, 716035.  
<https://doi.org/10.3389/fbioe.2021.716035>
- Dunky, M. (2023). Naturally-Based Adhesives for Wood and Wood-Based Panels. In *Biobased Adhesives* (pp. 517–578). John Wiley & Sons, Ltd.  
<https://doi.org/10.1002/9781394175406.ch19>
- Ebnesajjad, S. (2011). Material surface preparation techniques. *Handbook of Adhesives and Surface Preparation* (pp. 49–81). Elsevier.  
<https://doi.org/10.1016/B978-1-4377-4461-3.10005-7>
- Eisen, A., Bussa, M., & Röder, H. (2020). A review of environmental assessments of biobased against petrochemical adhesives. *Journal of Cleaner Production*, 277, 124277.  
<https://doi.org/10.1016/j.jclepro.2020.124277>
- Fahmy, Y., El-Wakil, N. A., El-Gendy, A. A., Abou-Zeid, R. E., & Youssef, M. A. (2010). Plant proteins as binders in cellulosic paper composites. *International Journal of Biological Macromolecules*, 47(1), 82–85.  
<https://doi.org/10.1016/j.ijbiomac.2010.03.012>
- Ferrandez-Villena, M., Ferrandez-Garcia, C. E., Garcia-Ortuño, T., Ferrandez-Garcia, A., & Ferrandez-Garcia, M. T. (2020). Properties of cement-bonded particleboards made from canary islands palm (*Phoenix canariensis ch.*) trunks and different amounts of potato starch. *Forests*, 11(5), 560. <https://doi.org/10.3390/f11050560>
- Ge, L., & Chen, S. (2020). Recent advances in tissue adhesives for clinical medicine. *Polymers*, 12(4), 939. <https://doi.org/10.3390/polym12040939>
- Han, R., Li, Y., Zhu, Q., & Niu, K. (2022). Research on the preparation and thermal stability of silicone rubber composites: A review. *Composites Part C: Open Access*, 8, 100249.  
<https://doi.org/10.1016/j.jcomc.2022.100249>
- Heinrich, L. A. (2019). Future opportunities for bio-based adhesives – advantages beyond renewability. *Green Chemistry*, 21(8), 1866–1888. <https://doi.org/10.1039/C8GC03746A>
- Hergenrother, P. M. (1990). *Polyimides as adhesives* (D. Wilson, H. D. Stenzenberger, & P. M. Hergenrother, Eds.; pp. 158–186). Springer Netherlands. [https://doi.org/10.1007/978-94-010-9661-4\\_6](https://doi.org/10.1007/978-94-010-9661-4_6)
- Hong, H. J., Gwon, K., Park, G., Yu, J.-H., Lee, S., Yu, J.-S., & Lee, D. N. (2025). Antibacterial and bio adhesive characteristics of mussel-inspired hyaluronic acid hydrogels encapsulated with sea urchin-shaped copper-coated silicon dioxide nanoparticles. *Carbohydrate Polymer Technologies and Applications*, 10, 100781.  
<https://doi.org/10.1016/j.carpta.2025.100781>
- Isikgor, F. H., & Becer, C. R. (2015). Lignocellulosic biomass: A sustainable platform for the production of bio-based chemicals and polymers. *Polymer Chemistry*, 6(25), 4497–4559.  
<https://doi.org/10.1039/C5PY00263J>
- Kajiyama, M. (2002). Chapter 17. The chemistry of bis-maleimides used in adhesives. <https://doi.org/10.1016/B978-044451140-9/50017-2>
- Kaybal, H., Ulus, H., & Avci, A. (2017). Influence of nano-CaCO<sub>3</sub> particles on shear strength of epoxy resin adhesives. *Uluslararası Muhendislik Araştırma ve Gelistirme Dergisi*, 29–35.  
<https://doi.org/10.29137/umagd.371119>
- Kinloch, A. J. (2012). Adhesion and adhesives: *Science and Technology*. Springer Science & Business Media.

- Kumar, A., Patil, P. B., & Pinjari, Dipak. V. (2025). Eco-friendly adhesives for wood panels: Advances in lignin, tannin, protein, and rubber-based solutions. *Journal of Adhesion Science and Technology*, 39(17), 2628–2669. <https://doi.org/10.1080/01694243.2025.2514151>
- K., U. (2023). Bioadhesives for clinical applications – a mini review. *Materials Advances*, 4(9), 2062–2069. <https://doi.org/10.1039/D2MA00941B>
- Lee, D., Hwang, H., Kim, J.-S., Park, J., Youn, D., Kim, D., Hahn, J., Seo, M., & Lee, H. (2020). VATA: A poly (vinyl alcohol)- and tannic acid-based nontoxic underwater adhesive. *ACS Applied Materials & Interfaces*, 12(18), 20933–20941. <https://doi.org/10.1021/acsami.0c02037>
- Li, L., Li, Z., Wang, Y., Li, X., & Li, B. (2021). Relation between adhesion properties and microscopic characterization of polyphosphoric acid composite SBS modified asphalt binder. *Frontiers in Materials*, 8. <https://doi.org/10.3389/fmats.2021.633439>
- Liu, M., & Chen, S. (2015). A novel adhesive factor contributing to the virulence of *Vibrio parahaemolyticus*. *Scientific Reports*, 5, 14449. <https://doi.org/10.1038/srep14449>
- Liu, Z., Liu, T., Li, Y., Zhang, X., Xu, Y., Li, J., & Gao, Q. (2022). Performance of soybean protein adhesive cross-linked by lignin and cuprum. *Journal of Cleaner Production*, 366, 132906. <https://doi.org/10.1016/j.jclepro.2022.132906>
- Luo, Y., Zhang, Z., Zuo, J., & Zhang, L. (2026). Research Progress in Chitin/Chitosan-Based Biomass Adhesives: Extraction Processes, Composite and Chemical Modification. *Polymers*, 18(3). <https://doi.org/10.3390/polym18030337>
- Mahnič, N., Pavlovič, B., Vidrih, R., Bohinc, K., Štukelj, R., Kovač, M., Bele, M., & Jeršek, B. (2024). *Penicillium* *Expansum* Adhesion to Materials Used in Food Industry. SSRN. <https://doi.org/10.2139/ssrn.4975059>
- Mardani, H., Roghani-Mamaqani, H., & Salami-Kalajahi, M. (2026). *Adhesive property of phenolic resins* (pp. 491–502). <https://doi.org/10.1016/B978-0-323-95660-4.00001-5>
- McDevitt, J. E., & Grigsby, W. J. (2014). Life Cycle Assessment of Bio- and Petro-Chemical Adhesives Used in Fiberboard Production. *Journal of Polymers and the Environment*, 22(4), 537–544. <https://doi.org/10.1007/s10924-014-0677-4>
- Messler, R. W. (2004). *Joining of Materials and Structures: From Pragmatic Process to Enabling Technology*. Butterworth-Heinemann.
- Nitu, I. P., Islam, M. N., Ashaduzzaman, M., Amin, M. K., & Shams, M. I. (2020). Optimization of processing parameters for the manufacturing of jute stick binderless particleboard. *Journal of Wood Science*, 66(1), 65. <https://doi.org/10.1186/s10086-020-01913-z>
- Perumal, V., Geetha, N., Palanivel, S., & Thulaseedharan, A. (2013). Natural rubber producing plants: An overview. *African Journal of Biotechnology*, Vol. 12, 1297–1310. <https://doi.org/10.5897/AJBX12.016>
- Pizzi, A. (2024). Unusual lignocellulosic bioresins: Adhesives and coatings for metals and glass. *Molecules*, 29(22), 5401. <https://doi.org/10.3390/molecules29225401>
- Pizzi, A. P. (2016). Natural adhesives, binders, and matrices for wood and fiber composites: chemistry and technology. In *Lignocellulosic Fibers and Wood Handbook: Renewable Materials for Today's Environment* (pp. 277–303). <https://doi.org/10.1002/9781118773727.ch10>
- Saha, N., Saha, N., Saha, T., Toksoy Öner, E., Brodnjak, U. V., Redl, H., Von Byern, J., & Saha, P. (2020). Polymer based bioadhesive biomaterials for medical application a perspective of redefining healthcare system management. *Polymers*, 12(12), 3015. <https://doi.org/10.3390/polym12123015>
- Sahoo, S., Mohanty, S., & Nayak, S. K. (2018). Biobased polyurethane adhesive over petroleum-based adhesive: Use of renewable resources. *Journal of Macromolecular Science, Part A*, 55(1), 36–48. <https://doi.org/10.1080/10601325.2017.1387486>
- Shadlou, S., Ahmadi-Moghadam, B., & Taheri, F. (2014). Nano-enhanced adhesives. *Reviews of Adhesion and Adhesives*, 2(3), 371–412. <https://doi.org/10.7569/RAA.2014.097307>
- Sineokov, A., Aronovich, D., Murokh, A., & Khamidulova, Z. (2008). Mechanism of Initiation of the Curing of Anaerobic Adhesives. *International Polymer Science and Technology*, 35, 31–38. <https://doi.org/10.1177/0307174X0803500705>
- Sini, N. K., Bijwe, J., & Varma, I. K. (2014). Thermal behavior of bis-benzoxazines derived from renewable feedstock ‘vanillin’. *Polymer Degradation and Stability*, 109, 270–277. <https://doi.org/10.1016/j.polymdegradstab.2014.07.015>
- Singh, M., Sethi, S. K., & Manik, G. (2022). Pressure-sensitive adhesives based on acrylated epoxidized linseed oil: A computational approach. *International Journal of Adhesion and Adhesives*,

- 112, 103031.  
<https://doi.org/10.1016/j.ijadhadh.2021.103031>
- Somani, K., Kansara, S., Patel, N., & Rakshit, A. (2003). Castor oil based polyurethane adhesives for wood-to-wood bonding. *International Journal of Adhesion and Adhesives - INT J ADHES ADHES*, 23, 269–275. [https://doi.org/10.1016/S0143-7496\(03\)00044-7](https://doi.org/10.1016/S0143-7496(03)00044-7)
- Sun, W., Tajvidi, M., Hunt, C. G., Cole, B. J. W., Howell, C., Gardner, D. J., & Wang, J. (2022). Fungal and enzymatic pretreatments in hot-pressed lignocellulosic bio-composites: A critical review. *Journal of Cleaner Production*, 353, 131659. <https://doi.org/10.1016/j.jclepro.2022.131659>
- Taboada, G. M., Yang, K., Pereira, M. J. N., Liu, S. S., Hu, Y., Karp, J. M., Artzi, N., & Lee, Y. (2020). Overcoming the translational barriers of tissue adhesives. *Nature Reviews Materials*, 5(4), 310–329. <https://doi.org/10.1038/s41578-019-0171-7>
- Takada, A., & Kadokawa, J. (2015). Fabrication and Characterization of Polysaccharide Ion Gels with Ionic Liquids and Their Further Conversion into Value-Added Sustainable Materials. *Biomolecules*, 5, 244–262. <https://doi.org/10.3390/biom5010244>
- Tout, R. (2000). A review of adhesives for furniture. *International Journal of Adhesion and Adhesives*, 20(4), 269–272. [https://doi.org/10.1016/S0143-7496\(00\)00002-6](https://doi.org/10.1016/S0143-7496(00)00002-6)
- Wang, Z., Chen, Y., Chen, S., Chu, F., Zhang, R., Wang, Y., & Fan, D. (2019). Preparation and characterization of a soy protein based bio-adhesive crosslinked by waterborne epoxy resin and polyacrylamide. *RSC Advances*, 9(60), 35273–35279. <https://doi.org/10.1039/C9RA05931H>
- Watcharakitti, J., Win, E., Nimnuan, J., & Smith, S. (2022). Modified Starch-Based Adhesives: A Review. *Polymers*, 14. <https://doi.org/10.3390/polym14102023>
- Wijaya, C. H., Wijaya, W., & Mehta, B. M. (2015). General Properties of Major Food Components. In P. C. K. Cheung & B. M. Mehta (Eds.), *Handbook of Food Chemistry* (pp. 1–32). Springer Berlin Heidelberg. [https://doi.org/10.1007/978-3-642-41609-5\\_35-1](https://doi.org/10.1007/978-3-642-41609-5_35-1)
- Xu, C., Xu, Y., Chen, M., Zhang, Y., Li, J., Gao, Q., & Shi, S. Q. (2020). Soy protein adhesive with bio-based epoxidized daidzein for high strength and mildew resistance. *Chemical Engineering Journal*, 390, 124622. <https://doi.org/10.1016/j.cej.2020.124622>
- Yu, J., Qin, Y., Yang, Y., Zhao, X., Zhang, Z., Zhang, Q., Su, Y., Zhang, Y., & Cheng, Y. (2023). Robust hydrogel adhesives for emergency rescue and gastric perforation repair. *Bioactive Materials*, 19, 703–716. <https://doi.org/10.1016/j.bioactmat.2022.05.010>
- Zazo, C. P., Gosselink, P., & Kromanis, R. (2025). Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) Analysis of Adhesives in Block-Glued Laminated Timber. *Sustainability*, 17(17). <https://doi.org/10.3390/su17178055>
- Zhang, W., Gao, Y., Zhou, Y., Wu, H., Suo, Z., & Lu, T. (2023). Strength and toughness of tissue adhesives depend on thickness. *Giant*, 16(100200). <https://doi.org/10.1016/j.giant.2023.100200>
- Zhang, Y., Chen, Q., Dai, Z., Dai, Y., Xia, F., & Zhang, X. (2021). Nanocomposite adhesive hydrogels: From design to application. *Journal of Materials Chemistry B*, 9(3), 585–593. <https://doi.org/10.1039/D0TB02000A>
- Zhang, K., Sun, H., Qian, Y., Shen, J., & Zhang, Z. (2025). Protein-Based Multifunctional Hydrogel Adhesive for Wound Healing. *Macromolecular Bioscience*, e00205. <https://doi.org/10.1002/mabi.202500205>
- Zhao, Y., Song, S., Ren, X., Zhang, J., Lin, Q., & Zhao, Y. (2022). Supramolecular adhesive hydrogels for tissue engineering applications. *Chemical Reviews*, 122(6), 5604–5640. <https://doi.org/10.1021/acs.chemrev.1c00815>
- Zhen, X., Cui, X., Al-Haimi, A. A. N. M., Wang, X., Liang, H., Xu, Z., & Wang, Z. (2024). Fully bio-based epoxy resins from lignin and epoxidized soybean oil: Rigid-flexible, tunable properties and high lignin content. *International Journal of Biological Macromolecules*, 254, 127760. <https://doi.org/10.1016/j.ijbiomac.2023.127760>
- Zhou, Y., Zeng, G., Zhang, F., Tang, Z., Luo, J., Li, K., Li, X., Li, J., & Shi, S. Q. (2022). Preparation of functional fiber hybrid enhanced high strength and multifunctional protein-based adhesive. *Materials & Design*, 224, 111289. <https://doi.org/10.1016/j.matdes.2022.111289>
- Zhu, Z., Zhang, E., Tu, Y., Ye, M., & Chen, N. (2022). An eco-friendly wood adhesive consisting of soybean protein and cardanol-based epoxy for wood-based composites. *Polymers*, 14(14). <https://doi.org/10.3390/polym14142831>
- Zhu, Z., Tu, Y., Ye, M., Zeng, Q., Rao, J., & Chen, N. (2023). A formaldehyde-free bio-composite sheet used as an adhesive with excellent water-wet bonding performance. *Industrial Crops and Products*, 198, 116680. <https://doi.org/10.1016/j.indcrop.2023.116680>