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Review Article

Selecting a Suitable Synthesis of Industrial Hot Melt Nanostructured Polyurethane Adhesives for the Enhanced Bonding of MDF and PVC Veneers - A Review

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ABSTRACT

This review focuses on the synthesis and application of industrial hot-melt nanostructured polyurethane adhesives (HMPUAs) used for enhancing the bonding of medium-density fiberboard (MDF) with polyvinyl chloride (PVC) veneers. The use of PVC veneers has been identified as an effective approach to protect wood composite products, particularly MDF, due to its resistance to moisture, environmental conditions, and cost-effectiveness. However, achieving strong adhesion between PVC and MDF remains challenging due to differences in their chemical and structural properties. This study compares various synthesis methods of polyurethane adhesives, emphasizing the prepolymer method as the most efficient approach for producing high-performance HMPUAs. Key challenges include optimizing the isocyanate to hydroxyl group ratio (NCO/OH), selecting appropriate polyols, and incorporating suitable additives. The effects of nanoparticles, including nanosilica, nanolignin, phosphorus, nitrogen compounds, mica particles, and aluminum trihydrate, on the mechanical and thermal properties of polyurethane adhesives are thoroughly discussed. Furthermore, the challenges of achieving consistent adhesive performance, compatibility, and durability under varying environmental conditions are addressed. The findings of this review provide essential insights into improving the synthesis of one-component HMPUAs and enhancing their applicability in MDF-PVC veneer bonding.

1. Introduction

Industrial growth and an increasing population, especially in developing countries, have significantly raised the demand for raw materials and production inputs. The scarcity of natural resources, particularly wood, has become a major concern, particularly for countries with limited forest reserves (Emadi et al. 2022; Fazeli et al. 2019; Hassani Khorshidi et al. 2024a; Sewagegn 2024). To address the shortage of wood resources and maintain competitive production processes, industries have explored various alternatives, including developing wood composite products (Aisyah et al. 2023). The wood composite industry focuses on utilizing less valuable lignocellulosic materials, such as agricultural and horticultural residues, to produce value-added products. Among these, Medium-Density Fiberboard (MDF) is one of the most important and widely used wood composites due to its cost-effectiveness, availability of raw materials, and desirable mechanical properties. MDF is manufactured through wet and dry processes, resulting in boards with densities ranging from 640 to 800 kg/m³ and thicknesses between 6 and 32 mm. While MDF can be made from various lignocellulosic sources, wood remains the most abundant and economical material for fiber production throughout the year. The quality of the final product can vary depending on the type and source of cellulose used, making the selection process crucial.

However, despite its advantages, MDF is highly susceptible to environmental degradation due to its heterogeneity and hygroscopic nature, which cause it to absorb moisture from the surrounding environment. This moisture absorption can lead to dimensional changes, mechanical weakening, and increased vulnerability to biological degradation by fungi and wood-eating insects (Hassani Khorshidi et al. 2024b; Lee et al. 2025). Additionally, exposure to moisture and biological agents often results in the formation of cracks, negatively impacting both the aesthetic appeal and structural integrity of MDF-based products. Given the limitations of natural wood resources and the growing demand for MDF, enhancing the durability of wood composite products has become a priority for industries. One effective approach to prolonging the service life of MDF is through the application of protective coatings. Industrial coatings are broadly classified into two categories: natural and synthetic coatings. Natural coatings are derived from thin layers of wood obtained by cooking wood in steam or hot water. These layers are then processed into decorative sheets or veneers. However, their application is limited due to low availability and high production costs.

In contrast, synthetic coatings are more commonly used and consist of various materials, such as decorative or nondecorative paper, thermoplastic sheets, and synthetic films. These materials are often applied to MDF using resins like melamine formaldehyde (MF) and phenol formaldehyde (PF), which enhance the mechanical and chemical stability of the product (Chrobak et al. 2022; Gadgeel et al. 2021). Among the various synthetic coatings, polyvinyl chloride (PVC) veneers have emerged as a highly effective method for protecting MDF. PVC veneers provide excellent resistance to moisture, adverse weather conditions, and chemical degradation, making them a popular choice in the wood composite industry.

Typically, PVC coatings are applied as layers with thicknesses ranging from 0.2 to 3 millimeters. They are produced from crude oil and chlorine gas, resulting in dense, flexible, and durable coating materials. Despite their many advantages, PVC veneers also have limitations. They tend to release toxic vapors when melted or burned, and their chemical resistance can be compromised when exposed to certain resins and heat during bonding processes. Consequently, achieving durable and effective bonding between PVC veneers and MDF requires the use of suitable adhesives. The most suitable adhesives for this purpose are polyurethane adhesives (PU adhesives), versatile materials widely used for bonding various substrates, including wood, metals, plastics, concrete, and brick. PU adhesives are known for their strong adhesion, flexibility, chemical resistance, and waterproof properties, making them ideal for many applications where other adhesives may fail (Gadhave et al. 2017, 2022).

Polyurethane adhesives are classified into the following categories:

1. One-component reactive adhesives that cure through reaction with air moisture.
2. Two-component reactive adhesives, which consist of polyisocyanate and polyol components, are mixed before application to form urethane bonds.
3. Solvent-based polyurethane adhesives, where polyisocyanates are dissolved in organic solvents to enhance their application.

4. Two-component solvent adhesives, which involve adding polyisocyanates as cross-linking agents.
5. Water-based dispersive adhesives, where polyurethane polymers are dispersed in water for environmentally friendly applications (Barikani et al. 2010).

PU adhesives are categorized as heat-cured, moisture-cured, or two-component systems, depending on their curing mechanism (Baskara et al. 2023). The hot-melt polyurethane adhesive (HMPUA) is particularly suitable for MDF-PVC bonding due to its rapid drying, high tensile strength, impact resistance, and UV stability. Additionally, HMPUAs can be formulated to cure at a wide range of temperatures, making them highly adaptable for various applications. The development of polyurethane adhesives dates back to 1930, when Otto Bayer first introduced them in Germany (Bayer 1953). Since then, extensive research has been conducted to improve the mechanical, thermal, and chemical properties of PU adhesives by adjusting the isocyanate to hydroxyl group (NCO/OH) ratio, selecting appropriate polyols, and incorporating various additives such as nanosilica, nanolignin, phosphorus and nitrogen compounds, mica particles, and aluminum trihydrate (Daemi et al. 2013; Eisen et al. 2020; Mohammadi et al. 2013, 2016).

Recent studies by Hassani Khorshidi et al. (2024a, 2024b) have investigated the use of lignin-based polyols for improving the environmental sustainability and mechanical properties of polyurethane adhesives. These findings provide valuable insights into the potential of bio-based polyols for enhancing adhesive formulations. The main objective of this review is to provide a comprehensive overview of one-component hot-melt polyurethane adhesives (HMPUAs) for bonding MDF with PVC veneers. This includes a comparative analysis of different synthesis methods, focusing on the prepolymer method, which offers the most promising results in terms of adhesive performance. Additionally, the review discusses the role of various additives in enhancing the mechanical and thermal properties of PU adhesives. Furthermore, a bibliometric analysis using VOSviewer was conducted to identify relevant studies and trends in the field. Keywords used for the analysis include “Polyurethane Adhesives,” “MDF,” “PVC Veneers,” “Hot-Melt Adhesives,” and “Nanostructured Adhesives.” The reviewed articles cover the period from 2000 to 2024, providing a comprehensive overview of recent advancements and remaining challenges.

2. Medium-Density Fiberboard (MDF) Coating Process

To increase the strength of the MDF, which is closer to that of natural wood, surface coatings with laminated paper and PVC at high hardening speeds can be used. This operation achieves favorable conditions when they are able to distribute and maintain the uniformity of density during the process. The uniformity of the density on the surface should be completely observed. Coating papers such as polyester, phenolic, and melamine-coated papers and PVC sheets are typically used for coating. To achieve ideal conditions, the humidity of the board should be greater than -6 and should not exceed 7% because it is difficult for water vapor to pass through this type of paper.

The rollers in the roller press are often raised pneumatically; these rollers are equipped with a digital controller system to adjust the panel’s density. Compressed air can be used for propulsion in the adhesive production system, the main part of which is the membrane pump (**Fig. 1**). The other equipment can be the input and output modules of pneumatic valves for temperature control, contactors, and PLC systems.

Fig. 1. Medium-density fiberboard coating process.

3. Introduction to Hot-Melt Polyurethane Adhesives

Hot-melt polyurethane adhesives are thermoplastic adhesives that, after use, chemically react with moisture in the air, which leads to a thermostatic state. This reaction creates a strong, durable bond that is resistant to heat, moisture, and chemicals (Yılgör and Yılgör 2020). These adhesives are mostly supplied in solid and one-component forms and require heat before application to activate their adhesive properties.

3.1. Properties and Benefits

Strong adhesion: When these adhesives are used on MDF panels, they penetrate the pores and sublayers of the wooden panel and create a strong and durable bond between the panel and the veneer that resists stress and environmental factors.

- Flexibility: After curing, adhesives retain some elasticity, which helps absorb stresses and accommodates slight movements or expansions in the bonded material. This flexibility is important when dissimilar materials such as MDF and PVC are combined, which may have different coefficients of expansion.
- Resistance to heat and humidity: Hot melt polyurethane (HMPU) adhesives exhibit very good resistance to heat and humidity after curing. This feature makes them ideal for use in environments with high temperatures and humidity fluctuations.
- Chemical resistance: Cured adhesives are resistant to various chemicals because of their strong urethane bonds (Choi et al. 2016; Pan et al. 2022).
- Speed of application: HMPU adhesives are set quickly after cooling and enable quick assembly, minimizing downtime in production processes (**Fig. 2**).

DSC analysis showed that the glass transition temperature (Tg) of the optimized HMPU samples increased from -48°C to -42°C with the addition of 2% nanosilica. Also, TGA testing showed that the thermal stability improved by 12% in the presence of aluminum trihydrate (Vega-Baudrit et al. 2007). **Table 1** compares the properties of Hot Melt Polyurethane (HMPU) adhesives with other adhesives, including Epoxy and Formaldehyde-based adhesives (UF and PF).

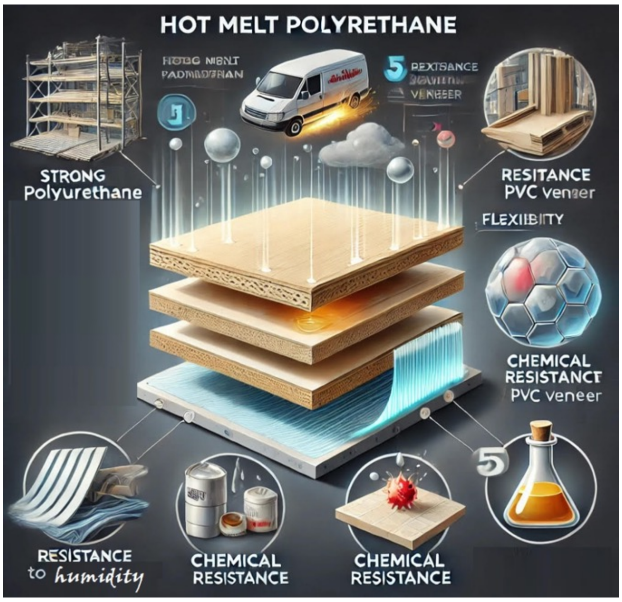

Fig. 2. Properties and benefits of hot melt polyurethane.

Table 1. A comparison of hot melt polyurethane (HMPU) adhesives with other adhesives, including epoxy and formaldehyde (UF and PF)

Properties	Polyurethane (HMPU)	Epoxy	Urea or phenol (formaldehyde)
Shear strength (MPa)	12.5	15.2	10.1
Moisture resistance (%)	95	98	70
Curing speed	At room temperature	Moderate	Requires heat
Thermal stability (°C)	Up to 300	Up to 350	Up to 200
Biodegradability	Adjustable with bio-based materials	Limited	Very limited
Production cost (USD/kg)	2.0–3.0	3.5–5.0	1.0–2.0
Advantages	High moisture resistance, fast curing, better biodegradability	High strength, excellent thermal stability	Low cost, wide availability
Disadvantages	Higher cost compared to formaldehyde, lower performance at high temperatures compared to epoxy	Low biodegradability, high cost	Low thermal stability and moisture resistance
Applications	Construction adhesives, protective coatings, foams	Composites, protective layers, industrial adhesives	Wood adhesives, low-cost composites

3.2. Historical Development and Early Research

The development of HMPU adhesives began with the need to overcome the limitations of conventional hot melt adhesives, which usually lack sufficient thermal and chemical resistance. Early research focused on formulating adhesives that could melt, flow and bond after cooling and be chemically engineered to form stronger amine, ester, ether, and urethane networks. Early studies explored the use of moisture-cured polyurethane systems that balance rapid initial bonding with the gradual development of strength and durability through moisture-induced curing processes.

Subsequent research delved deeper into the chemistry of HMPU adhesives. Considerable focus has been placed on the types of polyols and isocyanates used, as these components have important effects on the performance of the adhesive (**Table 2**). Researchers have investigated different polyol columns (such as polyether, polyester, and polycarbonate) to develop properties such as flexibility, adhesion strength, and resistance to environmental factors. Innovations have included the use of low monomeric isocyanates to reduce health risks and improve safety during handling and use (Kucinska-Lipka et al. 2017; Muhammad Zain et al. 2014; Vega-Baudrit et al. 2007).

Efforts to increase the performance of HMPU adhesives include the combination of different additives and fillers. Studies have investigated the effects of adding nanoparticles, such as silica or titanium dioxide, to improve the mechanical properties and thermal stability. In addition, combinations of plasticizers, stabilizers, and catalysts have been investigated to optimize the curing process and the final bond characteristics. Advances in formulation technology have resulted in adhesives with superior bond strength, flexibility under dynamic loads, and resistance to moisture and chemicals. Research has also explored various application techniques for HMPU adhesives to maximize their effectiveness in various industrial contexts. Additionally, advances in applicator equipment, including heated hose and nozzle designs, have contributed to more efficient and consistent application processes.

As environmental and health regulations have become more stringent, research into HMPU adhesives has increasingly focused on the greater stability and safety of these adhesives. Studies have aimed to develop formulations with more organic and less volatile compounds (VOCs). The trend toward biobased polyols derived from renewable sources represents a wider move toward greener and more sustainable adhesive solutions. In summary, the following is the rich and varied research background of hot melt polyurethane adhesives, which includes basic chemistry, performance optimization, production and application techniques, and environmental considerations. Continued innovation in this field promises to further increase the capabilities and applications of these versatile adhesives that meet the evolving needs of modern industries (Abid et al. 2020; Ecochard and Caillol 2020).

Table 2. Comprehensive development stages of HMPU adhesives

Year	Development stage
1937	First synthesis of polyurethane by Otto Bayer
1950s	Development of flexible and rigid polyurethane foams
1960s	Introduction of solvent-based polyurethane adhesives
1980	Introduction of hot melt polyurethane adhesives in the wood industry
1990s	Development of moisture-curable polyurethane adhesives
2000s	Emergence of solvent-free and environmentally friendly formulations
2010s	Integration of bio-based materials to enhance biodegradability
2020	Increased use of nanomaterials to enhance the performance of HMPU adhesives

3.3. Types of Materials and Improvements and their Applications in Polyurethane

Different materials and improvements are used in polyurethane for specific purposes. These purposes may serve legislators or industries. **Table 3** shows a general review of these materials and their effects on the properties of polyurethanes (Benin et al. 2014; Pinto et al. 2001; Wypych 2016; Zhang et al. 2015).

In the research by Mahmood et al. (2013), the use of isocyanates as additives in polyurethane adhesives resulted in a 15% improvement in adhesion strength between MDF and PVC. However, the study emphasized adhering to safety protocols due to health hazards associated with isocyanates. In another study conducted in a furniture manufacturing plant, replacing phthalate-based plasticizers with biodegradable plasticizers led to enhanced mechanical properties and reduced environmental risks. The adhesion strength improved, and thermal stability was also increased (Liu et al. 2019). In a research project by Zhang et al. (2020a), adding silica nanoparticles as fillers in polyurethane adhesives significantly improved the mechanical strength and thermal stability of the MDF-PVC bonding. However, careful control of particle size and uniform distribution was highlighted to prevent agglomeration and degradation of mechanical properties.

Table 3. Types of additives and reasons for their use

Additives	Reasons for use	Potential limitations or hazards
Isocyanates	These are used for polyurethane reactivity and curing properties	Potential toxicity, potentially harmful to health
Polyols	They have long and flexible segments that produce soft elastic polymers	-
Catalysts	They speed up the reaction between isocyanates and the polyols and allow the reaction to take place at lower temperatures	Cost considerations
Emollients	They reduce the hardness of materials	Can affect clarity and toughness
Pigments	They are used to produce colored polyurethane materials, especially for aesthetic purposes	-
Chain extenders	They modify the structure of polyurethane molecules and provide mechanical support that increases material properties	Possible brittleness; Cost considerations
Surfactants	They aid in the production of polyurethane foams, help control the formation of bubbles during synthesis and regulate the cell structure of foams	Possible brittleness; cost considerations
Flame retardants	They reduce the flammability properties of materials	-
Smoke inhibitors	They reduce the rate of possible smoke production when materials burn	-
Fillers	They minimize cost and improve material properties, such as hardness and tensile strength	Can affect clarity and toughness; poor dispersion can lead to defects

3.3.1. Isocyanates

The most important commercial polyisocyanates include toluene diisocyanate (TDI), diphenylmethylene diisocyanate (MDI), and hexamethylene diisocyanate (HDI), which are used as raw materials to produce polyurethane adhesives. Notably, these materials alone are not enough to produce adhesives. The other components of the adhesive mixture must be able to react quickly with the diisocyanate to form strong molecular cross-links in the network so that the highest adhesion and the best thermal resistance result. These materials should have relatively long pot lives. Isocyanates must be compoundable with other adhesive components to obtain a homogeneous and uniform mixture after the mixing process (Benin et al. 2014; Pinto et al. 2001; Sung et al. 2016; Zhang et al. 2015).

The most important factor in the production of one-component adhesives is the high reactivity of isocyanates with moisture. However, the reaction of low-molecular-weight polyisocyanates with moisture leads to the hardness and brittleness of the adhesive films, and the bonds are destroyed even at low stresses in the Perl test. Proper bonding results only with high-molecular-weight polyurethane isocyanates, such as isocyanate-terminated polyurethanes, which are called prepolymers and can be obtained with added isocyanates and polyester and polyether polyols with high molecular weights. Sufficient moisture is required to cure isocyanate-terminated polyurethane adhesives because these materials hardly react with moisture. This amount of humidity is at least 40% relative humidity, which must be created if it is not available (Adhikari et al. 2008; Jang et al. 2018; Quienne et al. 2021).

It should also be noted that exposure to isocyanates, particularly through inhalation or skin contact, can lead to serious health issues such as respiratory irritation, asthma, skin sensitization, and, in severe cases, chronic lung disease (Bello et al. 2007). To mitigate these risks, implementing stringent safety protocols in manufacturing environments is essential. These protocols include the use of proper ventilation systems, personal protective equipment (PPE) such as respirators, gloves, and safety goggles, as well as continuous air quality monitoring to assess isocyanate levels. Moreover, the replacement and elimination of isocyanates with safer alternatives have become a significant research focus in the industry, aimed at reducing health hazards and improving workplace safety.

3.3.2. Polyols

Polyols are widely used in different types to produce one-component reactive adhesives. Naturally enough, polyols designed to produce adhesives with special properties are preferred, especially polyester polyols designed in different types for reactive adhesives **(Table 4)**. Liquid polyols (polyalkylene adipate) with molecular weights in the range of 3000–500 are known to be suitable for specific uses in reactive adhesives (Ionescu 2005; Cross et al. 1975). The high polarity of the ester groups of these polyols results in special adhesion to many materials. Polyol PO_2 has particular properties, and this polyol has very good adhesion to plasticized PVC. Compared with polyester polyols, it is also considered preferable because of its low viscosity, which provides a special advantage for the production of low-solvent adhesives or solvent-free reactive adhesives (Chen et al. 2022; Cook 1978; Cross et al. 1975; Mahmood et al. 2013).

3.3.3. Other additives

To match the application of the adhesive, organic solvents such as ethyl acetate, stane, and methyl ethyl canene or, where nonflammable adhesives are needed, methylene chloride with trichloroethylene can be used. For some materials, such as plastics, reactive adhesives based on polyester polyols, polyethers, and polyisocyanates do not show satisfactory fluidization behavior even when a solvent is used. Moreover, adhesive coatings on the surface of the substrate are not distributed in the same way and form a fragmented and separated state.

Adding high-molecular-weight film ingredients such as hydroxylated polyurethanes results in better and more satisfactory fluidity properties in the adhesive. Cellulose derivatives such as cellulose acetobutyrate or nitrocellulose or vinyl acetate copolymers such as vinyl acetate and vinyl chloride maleic acid can also act in such a way that the latter material increases adhesion to the metal. White fillers such as talc, barite, fluorine, quartz, fluorine asbestos salts, or metal powders can participate in the reactions of urethane adhesives. These materials lower the price of products and reduce shrinkage during the adhesive curing process. These adhesives are usually used for materials such as wood, cement, metal, or plastic and must be completely dry and free of moisture (Azadeh et al. 2022; Cornille et al. 2017).

It is more reasonable that the fillers are mixed with polyol first, and then the polyol with the filler is involved in the adhesive reaction. These materials must be carefully diluted to avoid the formation of carbon dioxide, which drives the adhesive reaction toward foaming. In cases where strong absorbent materials are used, unacceptable penetration of adhesives takes place in these materials, which can be achieved by adding silica fillers as thixotropic agents.

Table 4. Comparison of polyether-based and polyester-based polyurethanes in terms of biodegradability

Criteria	Polyether-based polyurethane (PU)	Polyester-based polyurethane (PU)
Chemical structure	Contains ether linkages (C–O–C), which are relatively stable and hydrophobic	Contains ester linkages (C=O–O), which are more prone to hydrolysis
Hydrolytic stability	High resistance to hydrolytic degradation; suitable for humid environments	Low resistance to hydrolytic degradation; easily broken down by water or enzymes
Biodegradability	Poor biodegradability due to stable ether bonds	Good biodegradability due to the presence of hydrolyzable ester bonds
Oxidative stability	Susceptible to degradation by oxidation under UV light and in the presence of oxidizing agent	More resistant to oxidative degradation compared to polyethers
Applications	Preferred for outdoor applications requiring moisture resistance (e.g., coatings, sealants, adhesives)	Preferred for applications where biodegradability or controlled degradation is desired (e.g., biomedical materials, eco-friendly adhesives)
Environmental impact	Limited degradability; environmental accumulation is a concern	Higher degradability; less environmental accumulation
Modification potential	Can be modified with additives to enhance biodegradability, but effectiveness is limited	Easier to modify for improved biodegradability via copolymerization or blending with bio-based polyols
Cost	Generally lower cost and widely available	Often more expensive due to complex synthesis methods

In addition to being effective in diluting all components, additives such as rheolites, which are drying factors, can be added to polyol components. In this case, zeolite pastes are recommended because they are completely and quickly distributed in the adhesive and, in addition, are less sensitive to moisture than rhyolite powders are. Bonds formed in adhesives based on polyether, polyester, and polyisocyanate polyols are subject to aging. Adhesives with fewer transverse joints are weak against moisture penetration and high temperatures. Carbodiimide can increase the hydraulic degradation resistance of adhesive layers and is used in approximately 204% of cases. Tertiary amines can act as catalysts to increase the rates of cross-linking and curing (Azadeh et al. 2022).

3.3.4. Applications for improvers: nanosilica

In the study by Vega-Baudrit et al. (2007), with a focus on nanosilica, researchers achieved good results in terms of mechanical properties. They added 2% by weight nanosilica to a polyurethane elastomer adhesive and examined the obtained mixtures with different mechanical tests (**Table 5**). They concluded that the greater the silanol content, the greater the degree of phase separation in polyurethane. The degree of phase separation affects the thermal properties and crystallinity of polyurethanes (**Table 5**). Additionally, nanosilica increases the tensile strength and elongation at the break of polyurethane **(Fig. 3)**.

3.3.5. Application of mica and aluminum trihydrate

In the first stage, mixtures of polyurethane and mica with different percentages were prepared, and the optimal amount of mica used as a filler was evaluated in terms of mechanical properties. Then, aluminum trihydrate was added to the mixture of mica and polyurethane to prepare compounds with good flame resistance. The composition of mica was investigated in the range of phr 5–30, and it was observed that it is the best and provides important features such as high hardness and tensile strength and high wear resistance; however, the use of aluminum trihydrate led to a significant decrease in the tensile strength of aluminum trihydrate–polyurethane composites and aluminum trihydrate–polyurethane mica compared with those of the pure polyurethane and mica polyurethane composites. This is because aluminum trihydrate, unlike mica, is not a reinforcing filler for polyurethane, and large amounts are sufficient to provide a satisfactory flame retardant.

Table 5. Effects of nanosilica on the thermal properties of polyurethane

Nanosilica Polyurethane melting	**Temp. of glass transition (°C)**	**Crystallization temperature (°C)**	**Enthalpy crystallization (°C)**	**Melting temperature (°C)**	**Enthalpy of melting**
Without nanosilica	-49	-14	-22/3	47	30/8
0/45 mmol nanosilica	-48	-14	-22/2	46	26/5
0/6 mmol nanosilica	-49	-14	-22/1	44	25/8
0/9 mmol nanosilica	-48	-12	-22/2	45	23/3

According to the data obtained from the study by Vega-Baudrit et al. (2007), the combination (phr70–80) of aluminum trihydrate reduces the hardness, but adding phr 20 mica to phr 100 polyurethane results in less noticeable reduction values and, in addition, reduces the cost. As a result, owing to the decreasing effect of aluminum trihydrate on the mechanical properties, its use in some applications of polyurethane composites may be challenging. However, the addition of mica facilitates processing does not compromise the thermal behavior and reduces the final cost of the product.

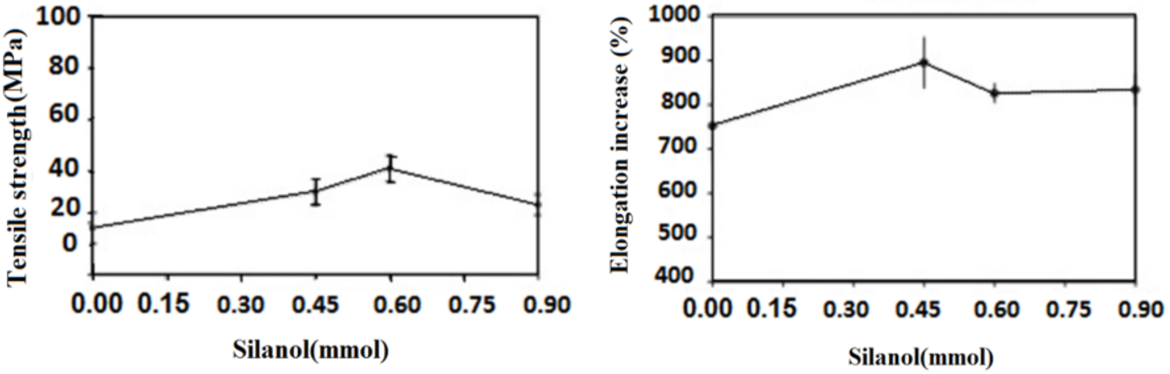

Fig. 3. Tensile strength and elongation of polyurethanes improved with nanosilica.

3.3.6. Application of phosphorus and nitrogen compounds

Owing to the sensitivity of polyurethanes to fire, they must be made resistant to fire and flame for their safe use. Usually, compounds based on halogens are added for this purpose. These compounds are not toxic or environmentally friendly. In addition, the use of halogenated compounds can reduce the mechanical properties. The study by Vega-Baudrit et al. (2007) has shown that polyurethane synthesized from phosphorus- and nitrogen-based materials can have the dual benefits of environmental protection and improved mechanical properties. Additionally, simple amine compounds with a polyamide with the help of a catalyst increase the degree of cross-linking and amines in combination with propylene carbonate lead to the expansion of strong urethane bonds.

3.3.7. Water-based hot melt polyurethane adhesives

Polyurethanes distributed in water consist of two main parts: the main body of the polyurethane chain and emulsifiers, hydrophilic materials, and polymers such as amphiphilic polyurethanes (e.g., grafted polyurethanes), which stabilize the distribution of polyurethane in water. Hard components with ionic groups play the role of hydrophilic parts, and soft components play the role of hydrophobic parts. These materials are divided into external and internal categories. Internal emulsifiers include nonionic centers such as polyethylene oxide and ionic anionic cationic centers and ion pairs (Ionescu et al. 2006; Rajendran et al. 1992; Sahmim et al. 2022).

Polyurethane dispersions stabilized in the nonionic form are obtained via diisocyanate-containing polyethylene oxide pendant chains. These dispersions are colloidally stable over a wide range of pH values, but a large concentration of comonomers based on polyethylene oxide is needed to obtain a dispersion with a small particle size. Sometimes, nonionic and anionic stabilization are used together to produce a dispersion with small particle size and strong stability at the same time without the need for an additional concentration of stabilizer. This type of polyurethane dispersion is prepared with acrylic latex-containing acid and at low pH.

Ionic groups enter the chain either in the form of the reaction agent of ionic DLs with ionic diisocyanates or through the polymerization of polyurethane with an ionic reagent. The obtained composition is called the polyurethane ionomer. Usually, DL with carboxylate, sulfonate, or salt ion groups is used as a quaternary ammonium emulsifier. For example, dimethylol propionic acid (DMPA) is used as an internal emulsifier in polymers and is then neutralized by a basic group such as triethylamine (TEA) (Honarkar and Barikani 2014).

This method of creating hydrophilic groups is called an internal emulsifier or self-emulsifier and has three advantages:

1. Polyurethane molecules whose hydrophilicity has been modified can be dispersed under mild conditions.
2. Dispersion with a smaller particle size is obtained, and as a result, its stability increases.
3. Films obtained from dispersions have better resistance to solvents and water.

Therefore, the hydrophilicity of the ionic groups results in the dispersion of polyurethane in water (without the use of an external emulsifier). Polyurethane ionomers have the advantages of polyurethanes and ionomers (polyurethane ionomers) (Honarkar and Barikani 2014). As mentioned earlier, ordinary polyurethanes are often hydrophobic, but by introducing ionic hydrophilic components into the polyurethane chains, it is possible to disperse or emulsify the polyurethane. The synthesis and properties of ionomers and their use, especially in water environments, have been discussed in review articles (Szycher 2013; Zhang et al. 2020b). In industry, polyurethane dispersions are obtained in several ways. These processes include emulsification or suspension processes, acetone processes, thermoplastic processes, prepolymerization, and ketimine-ketazine processes (Strøbech 1990; Zhou et al. 2015).

3.4. Emulsification Process or Prepolymer Suspension

In the process of emulsification or prepolymer suspension, polymerization is performed in a water bath at a constant temperature of 38–40°C. For example, polypropylene glycol (PPG) and dimethylol propionic acid (DMPA) in DMF are poured into a dry reactor at 70°C for 30 minutes to obtain a homogeneous mixture. Isofuran diisocyanate (IPDI) and dibutyltin dilaurate (DBTDL) catalysts were added dropwise, and the mixture was stirred for another 30 minutes at 70°C. The temperature was subsequently raised to 80°C, and three hours were allowed to obtain the NCO-terminated prepolymer. In the next step, the reaction mixture was cooled to 60°C, and triethylamine (TEA) was added as a neutralizer. Then, the chain extension was added for one hour, and in the last step, water was added at 30°C. In this reaction, a dispersion is obtained with 40% solids (Jhon et al. 2001; Nasrullah et al. 2009).

3.4.1. Ketamine ketazine process

The ketamine-ketazine process is another type of prepolymer mixing process. The chain-extending agent is a ketone-blocked diamine (ketimine) or ketone-blocked hydrazine (ketazine), directly reacting with the NCO-terminated prepolymer. During the water dispersion stage, ketimine or ketazine is hydrolyzed, diamine or hydrazine is released, respectively, and chain extension occurs. This method is more suitable for preparing polyurethane dispersions based on cyclic diisocyanates with high reactivity with water, an advantage over the prepolymer mixing process (Guo et al. 2013; Nelson and Long 2014).

3.4.2. Hot melt process

The hot melt process includes capping the prepolymer with NCO end by urea at more than 130°C to form biurea. Capped polyurethane (which may be free of solvent) is dispersed in water at a temperature of approximately 100°C to minimize viscosity, and chain extension in the vicinity of water is performed by the formation of formaldehyde and methylol groups; in the process of polyurethane concentration polymerization, urea is obtained (Manvi and Jagtap 2010; Mishra et al. 2010).

3.4.3. Acetone process

In this process, for example, polysterol and dimethylol propionic acid (DMPA) are poured into the reactor colleagues (Lee et al. 2012; Shin et al. 2013). While stirring, acetone was added to obtain a homogeneous mixture, isophorane diisocyanate (IPDI) and a few drops of dibutyltin dilaurate (DBTDL) were added, and stirring was continued at 60°C. In the next step, DL butane reacts as a chain extender; the polymerization reaction is complete after two hours. The final polymer was neutralized with triethylamine and stirred for another 30 minutes at 55°C. In the last step, water is slowly added, and after half an hour, the reaction mixture is transferred to the rotary evaporator, and the acetone is evaporated at a temperature of 35°C and a vacuum of 70 mmHg. The prepolymer emulsification process is mostly used to synthesize urethane particles in the coating industry, whereas the acetone process is used to prepare urethane particles in adhesive applications. The acetone process is shown in **(Fig. 4)**.

The prepolymer suspension and acetone processes are the most commonly used in the preparation of water-based polyurethanes. For example, water-based polyurethanes with different solid contents of up to 50% have been synthesized by Li and colleagues (Shin et al. 2013). The synthesis of prepolymers based on IPDI and poly-1-butylene adipate glycol (PBA) with different molecular weights (3000) and Mn values of 2000 and 1000 was carried out through the acetone process. Effects of the amount of DMPA, NCOOH molar ratio, and molecular weight of DL (soft phase). The properties of polyurethane were investigated by dynamic light scattering, which revealed that by increasing the amount of DMPA, small particles with a narrow distribution were obtained, and the molar ratio of NCO/OH, which plays an important role in controlling the particle size, decreased. When the particle size reaches a maximum value at a ratio of NCO/OH=1.7, the particle size decreases sharply in the polyurethanes obtained from DL. When the molecular mass is 1000 or 2000 g/mol, the particles are spherical, but when the molecular mass of the polyol increases, the particles are elongated and irregular. Currently, the use of fast and automatic methods comparable to laboratory methods is preferred. These methods have been used to produce polyurethane dispersions. In this way, polyurethane synthesis experiments are carried out using process factors to optimize the applicable method in the automatic reactor system to create the desired properties in the final product. Another advantage of this system is that it creates identical results through the intermediary. The controlled introduction of a water neutralizer and an increasing number of chain studies have shown that the rate of water addition is the most important factor in the final properties of the product. This research provides useful methods for optimizing the properties of aqueous polyurethanes and the final properties of the product, including the particle size.

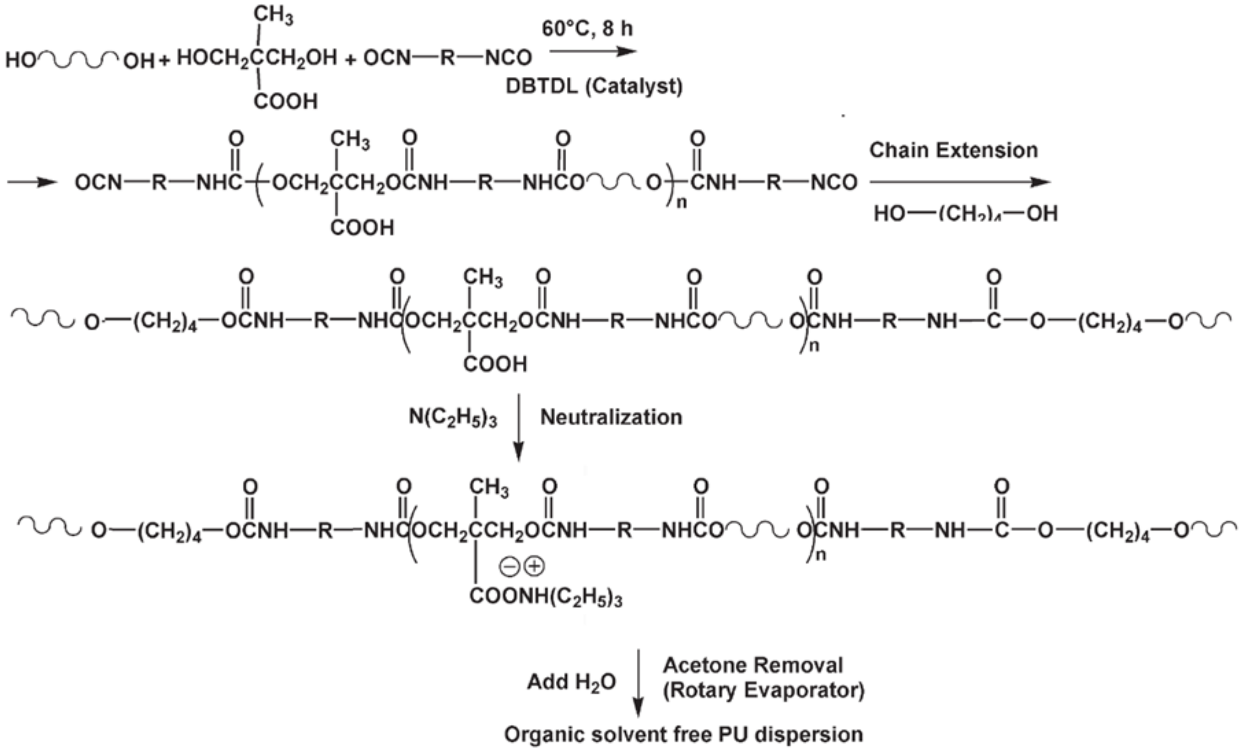

Fig. 4. Acetone process: polysterol and dimethylol propionic acid (DMPA) are poured into the reactor colleagues.

3.4.4. Solvent-free, hot melt-reactive polyurethane adhesives

Solvent-free synthetic reactive polyurethane thermoplastic adhesives are made from a blend of polyester, polyether, and, in rare cases, polycarbonate polyols. Polyester polyols have excellent adhesion properties, high tensile strength, and heat resistance, and they provide crystalline properties to hot-melt polyurethane. However, they have poor hydrolytic stability. In addition, a high percentage of polyurethanes are obtained from polyether polyols because of their low price and easy handling, in addition to high hydrolytic and chemical resistance. They provide flexibility to the adhesive but are susceptible to oxidation under UV light (Fang et al. 2013).

Polyether and polyester polyols are more widely used because of their lower production cost but have limited advantages. The polyether and polyester are replaced by polycarbonates. Polyurethanes obtained from these polyols have excellent hydraulic stability, high chemical resistance, improved durability, high thermal stability, good properties at low temperatures, and good mechanical properties. The production cost of these materials is greater than that of polyether and polyester. For this reason, they are used in high-performance applications (Gosselink et al. 2004; Li and Sun 2007). Solvent-free hot melt polyurethane adhesive formulations typically contain approximately 5 to 50% by weight of an isocyanate, a polyol blend that can include 10 to approximately 60% polyether, 0 to approximately 40% polyester, and 0 to approximately 50% acrylic polyol (Gosselink et al. 2004; Li and Sun 2007)

The polymeric isocyanates that may be used in the practice of the invention are aromatic or aliphatic. The aromatic isocyanate oligomers preferably have 2 or more repeated units. Isocyanates are usually added in amounts ranging from approximately 1 to 20% of the polymer to improve wood adhesion effectively. An increase in isocyanate content leads to an increase in shear strength. Wang et al. (2020) synthesized a solvent-free hot melt polyurethane adhesive via the Diels–Alder reaction. They reported that this resin is thermoplastic and exhibits noncovalent hydrogen bonds. The furan ring-terminated polyurethane prepolymer was synthesized through a three-step process.

First, N,N-carbonyldiimidazole (CDI) (1.6 g, 10 mmol) with polytetramethylene ether glycol (PTMG) (0.5 g, 5 mmol) was reacted in 10 ml of N,N-dimethylformamide (DMF) under a nitrogen atmosphere at room temperature for 1 hour. In the second step, furfurylamine (FA) (1 g, 10 mmol), dissolved in 2 ml of DMF, was added dropwise to the solution in an ice water bath and kept there for 5 hours at 80°C. The solution was then poured into deionized water to remove the byproduct, and the PMCF product was purified with dichloromethane, yielding a light yellow viscous liquid (5.5 g, yield: 92%). Finally, the mixture of hot melt polyurethane adhesive with the PMCF DA additive (CDI-PUR-DA) (5.5 g, 4.6 mmol) was dissolved in DMF and reacted with BMI (1.7 g, 4.6 mmol) under a nitrogen atmosphere at 60°C for 4 hours. The resulting synthetic adhesive was evaporated in an oven at 50°C to obtain a flat yellow polyurethane film (7 g, yield: 97%).

In another study, Tian et al. (2011) developed a thermoplastic polyurethane (TPU) hot melt adhesive using polybutylene adipate (PBA) as a soft part, and methane-4-4-diisocyanate (MDI) and 1,4-butanediol (BDO) were synthesized as hard parts. The details of this project are as follows: First, a polyol polyester (PBA) with an average molecular weight of 3000 g/mol and Methane-4,4'-diphenyl diisocyanate was supplied. The butanediol (BDO) chain developer from Kermel Chemical Reagent Co., Ltd. (Tianjin, China) was purchased. Industrial pentaerythritol abitate was also supplied by Baolin Chemical Industry Co. Foshan, China. C9 petroleum resin was of industrial type and was obtained from the German company Petroleum Resins Co. The industrial CaCO3 antioxidant had a reagent grade 1010 and was purchased from Yingao Trade Co. The mixture of thermoplastic polyurethane adhesive in this study was synthesized in two steps. The first stage of polyurethane prepolymer synthesis is shown in (**Fig. 5**).

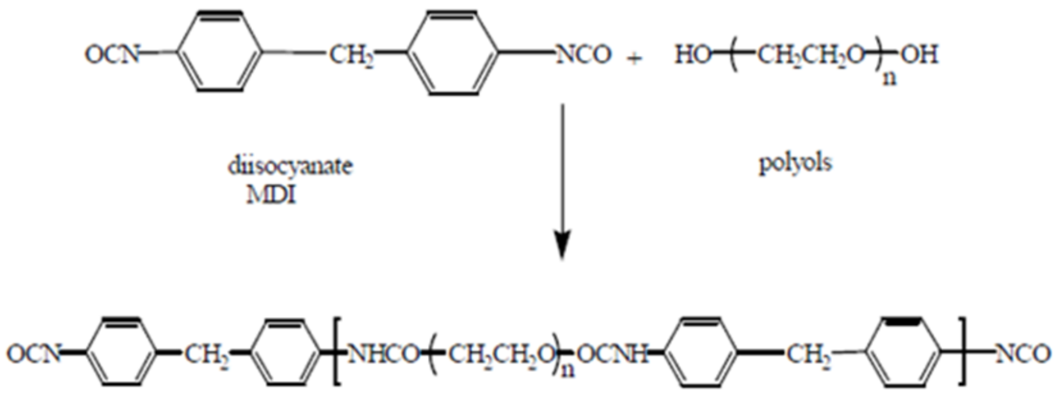

Fig. 5. Prepolymer terminated with isocyanate.

The second step was the synthesis of thermoplastic polyurethane elastomer (i.e., hydroxy-terminated polyurethane) (**Fig. 6**).

$$\text{NCO-R'-NCO} \quad + \quad (\text{OH})_n\text{R''} \longrightarrow \text{OH-R'-NHCOOR''-OH}$$

isocyanate-terminated prepolymer chain extender (n=2) thermoplastic polyurethane

Fig. 6. Polyurethane with a hydroxy terminal.

Poly-butylene glycol adipate diol (PBA) was dehydrated under vacuum at approximately 115°C for 2 hours and then poured into four flasks with an electric stirrer, heating equipment, and thermometer. Once the temperature was decreased to 50–60°C and accurate measurements were taken, premelted MDI was added, and the mixture was attached. The weighed PBA was dehydrated under vacuum at approximately 115°C for 2 hours and then poured into four flasks with an electric stirrer, heating equipment, and thermometer. When the temperature was decreased to 50–60°C, premelted MDI was added to the four flasks under N_2 gas.

Under N_2 gas pressure, the reaction system was slowly heated to 85°C in four flasks for 2–3 hours. Then, some samples were taken, and the NCO content was determined. A chain extender can be added if it is essentially equal to the theoretical value and standards (Lei et al. 2014). The reaction system was stirred at high speed for 5 to 10 minutes. Next, the samples were poured into the mold and kept under vacuum at 110 ± 5°C for 4 hours. Finally, the samples were incubated at room temperature for 7 days, after which thermoplastic polyurethane elastomer was prepared.

In the second step, a certain amount of synthesized polyurethane thermoplastic elastomer was used to prepare thermoplastic polyurethane adhesive. A part of this elastomer was weighed and then placed in the human body. Additionally, adhesive resins, fillers, antioxidants, and other additives that were dried were poured into the container. The mixtures were subsequently heated to a liquid state and stirred uniformly. Finally, the hot melted adhesive was obtained and stored hermetically. The solid thermoplastic polyurethane adhesive was repeatedly rolled on a two-roll open mill to a specific thick layer. Adhesive bonding was achieved by pressing the film between two standard steels at 150°C for 10 minutes in a 0.5 MPa press. The thickness of the band line was maintained at 0.1 mm. After assembly of the edge joints, all the substrates were cooled at room temperature for 24 hours. The shear strength was measured via an electronic tensile machine at a speed of 5 mm/min according to the standard GB4587-1979. The results showed that the shear strength of the thermoplastic adhesive synthesized with pentaerythritol abitate was greater than that with C9. When the content of pentaerythritol abitate was 20% by weight, the shear strength of the thermoplastic adhesive reached a maximum (9.27 MPa). The results also indicated that increasing $CaCO_3$ content decreases shear strength. Since the initial decomposition temperature of the PU mixtures was approximately 260°C, their heat resistance properties were also estimated to be reasonable (Behroz et al. 2011; Perez-Arce et al. 2020).

In another study, McCreath et al. (2022) synthesized a propylene glycol-based and propylene glycol-transparent polyurethane laminate adhesive. For this purpose, the following materials were used as soon as received: 4,4-MDI, IPDI, dibutyl tin dilaurate (DBTDL), triethylamine (TEA), isopropyl alcohol (IPA), and ethanolamine (EA). TMP, DEPD, BD, PD, and PPG with a molecular weight of 1000 were dried at 80°C under vacuum before use. A bisphenol-A polycarbonate (PC) film with a thickness of 175 µm was applied (Perez-Arce et al. 2020). Next, prepolymer synthesis was carried out in a reaction kettle equipped with a nitrogen inlet, nitrogen outlet, overhead mechanical stirrer, k-type thermocouple, and reactant addition inlet. Polyurethane (PU) prepolymer synthesis was performed in one or two synthetic steps.

In the first step, a mixture of PPG with 10 mol% of the triol chain extender TMP (calculated from the moles of OH in PPG) was added to the reaction kettle and allowed to equilibrate at 90 ± 5°C for 30 minutes. The stirring of MDI or IPDI was continued at a stoichiometric ratio of 0.2:2 (NCO:OH), and the mixture was added to control the exothermicity of the reaction and to ensure that the temperature did not exceed 95°C. Note that MDI is a solid and must be melted in a separate container at 50°C under a nitrogen atmosphere for 3 hours for the diisocyanate-based adhesive MDI and stirred for 5 hours for the IPDI-based adhesive. The TMP formulation was completed at this stage, and after the addition of curing catalysts with 0.05 wt% of the total batch weight, 0.05 wt% TEA (DBTDL) and degassing were completed at 50°C under vacuum. The PU prepolymer was then transferred to an aluminum cartridge and stored under vacuum at 5°C until use. The formulation was used within one month after synthesis.

Finally, each PC film was subjected to surface modification using a 70:30 solution containing IPA: EA. The treatment mixture was applied by wiping the film surface for 2 minutes, followed by a 1-minute rest period to allow the solvent to evaporate, and then the mixture was placed in an oven at 120°C for 2 minutes. After removal from the oven, the surface treatment was complete, and the films were ready for adhesive application. The results showed that the difference in microphase mixing did not have a consistent effect on the obtained peel strength; only 31% of the tested sheet composites had a peel strength of less than 3 N/mm after 18 months. DL chain-extended formulations based on methylene diphenyl diisocyanate had 25% lower resistance (Behroz et al. 2011; Perez-Arce et al. 2020). A comparison of the strengths and biocompatibility of various polyurethane synthesis methods is given in (**Table 6**).

4. Synthesis of Biodegradable Polyurethanes

Biodegradable polyurethanes are a group of polyurethanes prepared from polyols with biodegradable properties, such as biodegradable polyurethanes based on starch (**Table 7**) (Zhang et al. 2013). Polycaprolactone, fatty acid esters, polylactic acid nanolignin, castor oil, palm oil, and soybean oil (Zhao and Umemura 2014). The diisocyanates used in the production of biodegradable polyurethanes can react with the alcohol groups of polyol, similar to the production of conventional polyurethanes, and lead to the production of urethane groups, or they can act as chain extenders. In this case, the polyesters used in the production of polyurethane are polyesters with low molecular weights, the prepolymer and diisocyanate act as chain extenders, and polyurethane with high molecular weights is prepared (Wang et al. 2019; Wang et al. 2020). Biodegradable polyurethanes are prepared from biocompatible polyesters (Yue et al. 2011; Xie et al. 2021).

Table 6. Comparative table of polyurethane synthesis processes with numerical data

Process	Adhesion strength (MPa)	Thermal stability (°C)	Biodegradability (%)	Production cost (USD/kg)
Water-based polyurethane adhesives	6.5–8.0	Up to 220	Over 80 (in 12 weeks)	1.2–1.8
Solvent-based polyurethane adhesives	10.0–12.0	Up to 300	Less than 5 (in 12 weeks)	2.5–3.5
Ketamine-ketazine process	7.0–9.0	Up to 280	Not Evaluated	1.5–2.5
Hot melt process	8.0–10.0	Up to 290	Less than 10 (in 12 weeks)	2.0–3.0
Acetone process	7.5–9.5	Up to 270	Less than 5 (in 12 weeks)	1.8–2.8

They have been widely used and tested in industrial applications. Importantly, despite the good mechanical properties and biocompatibility of this type of polyurethane, its long-term molecular stability in the living environment is limited. The destruction of these materials is accomplished through chemical or enzymatic hydrolysis of their aliphatic ester connection. The stability of polyether polyurethanes against hydrolysis is greater than that of polyester polyurethanes, but polyether polyurethanes can be degraded both by oxidation processes and by hydrolysis processes that can be accelerated by enzymes. According to Chen et al. (2020), biodegradable resins should be used for industrial products. The latter is preferred because it is an abundant, inexpensive, nonedible, and low-toxicity renewable resource (Wang et al. 2017).

Table 7. Comparison of lignocellulose-based and industrial polyurethane adhesives

Feature	Lignocellulose-Based Adhesives	Industrial Adhesives (Polyurethane)
Shear strength (MPa)	7.2 (average), Range: 6.0 - 8.5	12.5 (average), Range: 11.0–14.0
Thermal stability (°C)	Up to 220 (50% weight loss at 320°C)	Up to 300 (50% weight loss at 400°C)
Biodegradability	High (over 80% degradation within 12 weeks)	Low (less than 5% degradation within 12 weeks)
Production cost (USD/kg)	1.2–1.8	2.5–3.5
Raw materials	Lignocellulosic waste (lignin, cellulose)	Petrochemical materials (polyols, isocyanates)
Chemical modification methods	Oxidation, acetylation, amination, graft polymerization	Use of various polyol chains, enhancement with fillers and nanoparticles
Chemical structure	Contains phenolic, carboxylic, and hydroxyl functional groups	Contains polyol (hydroxyl) chains and isocyanates (NCO)
Advantages	High biodegradability, lower cost, renewable resources	High strength, better thermal stability, structural diversity
Disadvantages	Lower strength, limited thermal stability, dependent on chemical modification	Higher cost, non-biodegradable
Applications	Wood adhesives, biocomposites, flooring	Construction adhesives, protective coatings, foams

In another study, Daneshvar et al. (2021) synthesized polyurethane adhesive from lignocellulosic waste via liquefaction (Yu et al. 2021). To prepare the polyol, ethylene carbonate was used as a solvent, 98% sulfuric acid was used as a catalyst, and sawdust of beech wood with a particle size that passed through a mesh of 40 and remained on a mesh of 60 was used. Additionally, to prepare wood adhesive from polyurethane, 4,4 diphenylmethane diisocyanate polymer (PMDI) and 2,4 and 2,6 toluene diisocyanate (TDI) and dibutyl tin dilaurate and glycerol were used.

Next, to liquefy and prepare the polyol, first, ethylene carbonate and 98% sulfuric acid were poured into a three-well flask equipped with a condenser, thermometer, and stirrer, and it was placed inside a preheated oil bath (**Fig. 7**). After the temperature of the mixture inside the balloon reached 110–160°C, oven-dried beech wood sawdust (with zero percent humidity) was added (weight ratio of lignocellulosic material to solvent: 1:5). The liquefaction time was considered the time from which sawdust was added to the contents of the balloon. After the end of the liquefaction time to stop the process, the balloon was placed in cold water for 3 spans of 20, 40, and 60 minutes, with a catalyst amount of 3%. The liquefaction process was then continued at the optimized temperature and at 40, 60, 90, 120, and 180 minutes to determine the optimal liquefaction time with a 1.5% catalyst (Mohammadi et al. 2015; Akindoyo et al. 2016).

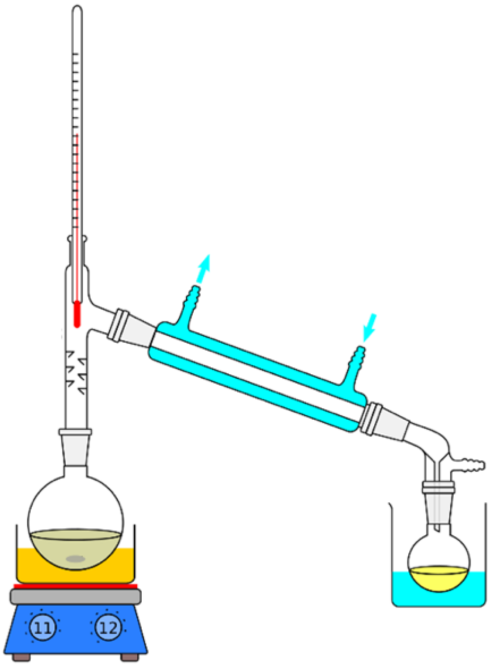

Fig. 7. Schematic image of the liquefaction process system.

To prepare a polyurethane wood adhesive and determine the optimal amount of catalyst and glycerol, first, polyols prepared with glycerol as a crosslinker and dibutyltin dilaurate as a catalyst were mixed for 1 min by a mixer at a speed of 200, and then isocyanate was added to the mixture and stirred for 3 min at the same speed as before (Akindoyo et al. 2016; Yu et al. 2021). The optimal amounts of glycerol and catalyst were determined in the ranges of 1–5 and 0.1–0.5, respectively, on the basis of the weight of the adhesive by measuring the gelation time and shear strength via the response surface methodology (RSM) statistical method. Notably, to determine the optimal amount of catalyst and glycerol, the NCO/OH molar ratio was considered equal to one (Zhao and Umemura 2014). After the optimal conditions for the preparation of the TDI and PMDI polyurethane adhesives were determined, they were prepared with different NCOOH molar ratios (1.7, 1.5, 1.3, 1, 0.7).

The results obtained from the preparation of polyurethane wood adhesives with different molar ratios of NCOOH showed that by increasing the amount of isocyanate in the adhesive mixture, the shear strength of the adhesive increased, and a molar ratio of NCO/OH = 1.7 resulted in the highest shear strength. Furthermore, the shear strength of the PMDI polyurethane wood adhesive is greater than that of the TDI polyurethane wood adhesive. Additionally, the results revealed that the shear strength of the polyurethane adhesive of the control sample was greater than that of both types of polyurethane wood adhesive because of the presence of more hydroxyl groups in the industrial polyols. Researchers have reported that the low shear strength of polyurethane wood adhesive compared with that of industrial polyurethane adhesive is due to the low number of hydroxyl groups and impurities. Therefore, these compounds prevent the formation of strong hydrogen bonds with isocyanate and reduce the shear strength of the adhesive (Abdollahi 2017; Daneshvar et al. 2021). **Table 7** compares the bond strength and thermal stability of lignocellulose-based and industrial adhesives (polyurethane). Information on chemical modification methods and chemical structure is also provided.

5. Conclusions and Future Challenges

This study reviewed one of the most common protection methods in the wood composite industry, focusing on using PVC veneers to enhance the durability and mechanical performance of medium-density fiberboard (MDF). While two-component polyurethane adhesives have advantages, their preparation process is time-consuming, costly, and prone to errors during mixing. Therefore, developing one-component and hot-melt polyurethane adhesives was highlighted as a practical approach to simplify the process and improve efficiency. The research demonstrated that effective bonding in reactive adhesives largely depends on the high molecular weight of polyurethane isocyanates, particularly isocyanate-terminated prepolymers formed by adding isocyanates to high-molecular-weight polyester and polyether polyols. These prepolymers exhibit enhanced reactivity due to the increased number of phenolic and aliphatic hydroxyl groups, resulting in stronger physical and chemical interactions within the polyurethane matrix.

Additionally, the choice of polyols and their design for producing adhesives with specific properties, especially polyester polyols, plays a critical role in achieving desirable adhesion characteristics. Optimizing the NCO/OH ratio during the synthesis of polyurethane adhesives is also essential for improving their mechanical performance. Future research should focus on developing sustainable polyurethane adhesives using bio-based polyols, such as lignin-derived polyols, to reduce environmental impact. Additionally, the scalability of one-component polyurethane adhesives for industrial applications should be investigated, including optimizing formulations for enhanced thermal stability, mechanical strength, and environmental resistance. Exploring advanced additives and modification techniques, such as nanofillers or reactive flame retardants, can further improve the performance and broaden the application scope of these adhesives.

Author Contributions

All authors contributed equally to various aspects of this study, including conceptualization, methodology, data collection, analysis, manuscript writing, and revision. Each author played a significant role in ensuring the accuracy, integrity, and quality of the final manuscript. All authors have read and approved the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest. The funding sponsors had no role in the selection of the research topic, study design, data collection, analysis, interpretation, manuscript writing, or the decision to publish the results.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the author(s) used ChatGPT to refine and improve certain aspects of the manuscript, specifically to address minor linguistic and structural inconsistencies in the scientific text. The AI tool was not used for generating original ideas, data analysis, or substantive content creation. After utilizing this tool, the author(s) carefully reviewed and edited the content to ensure accuracy and coherence, taking full responsibility for the final version of the manuscript.

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