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Synthetic Adhesives in Production of Engineered Wood Products: A Review

Sintetička ljepila u proizvodnji kompozitnog drva: pregled literature

REVIEW PAPER
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ABSTRACT • *Adhesives used in the production of wood composite materials, including engineered wood, are a significant component that characterizes the performance of the final products. Also, the adhesive type, quantity and properties significantly impact the cost of the resulting materials. The aim of this review was to present some of the basic characteristics of bonding agents for engineered wood. Based on the information provided, a suitable adhesive can be selected to form final products that meet the needs of consumers. Therefore, it is of essential importance to know the advantages and disadvantages of adhesives, since global trends require the creation of environmentally friendly products. The latter must contain a minimum amount of free formaldehyde. The object of this review was to deliver an analysis of the most commonly used synthetic resins in the production of engineered wood products (EWPs), namely amino based, phenolic based, isocyanate, polyurethane and polyvinyl acetate.*

KEYWORDS: *bonding agents, construction industry, composite materials, properties*

SAŽETAK • *Ljepila koja se rabe u proizvodnji kompozitnog drva važna su komponenta koja utječe na svojstva gotovih proizvoda. Osim toga, vrsta, količina i svojstva ljepila uvelike utječu na cijenu proizvedenih materijala. Cilj ovog rada bio je predstaviti neka osnovna svojstva ljepila za kompozitne materijale na bazi drva. Na temelju iznesenih informacija može se odabrati prikladno ljepilo za izradu proizvoda koji zadovoljavaju potrebe potrošača. Stoga je iznimno važno znati prednosti i nedostatke ljepila jer globalni trendovi zahtijevaju izradu ekološki prihvatljivih proizvoda. Oni moraju sadržavati minimalnu količinu slobodnog formaldehida. Cilj ovog rada bio je provesti analizu najčešće upotrebljavanih sintetičkih smola u proizvodnji kompozitnog drva (EWP) na bazi aminokiselina i fenola, izocijanata, poliuretana i polivinil acetata.*

KLJUČNE RIJEČI: *vezivo; građevna industrija; kompozitni materijali; svojstva*

1 INTRODUCTION
1. UVOD

All areas of our lives are developing, and this leads to a growing share of the construction industry (FAO, 2022). The main components in the creation of the structural elements of these facilities are bricks, concrete, steel, but in recent years wood is also increasingly used (Švajlenka and Pošiváková, 2023).

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Wood as a structural element has always been one of the most popular, practical and economical building materials (Senft, 2002). Even today, wood constructions are preferred not only because of the lower financial investment, but also because of their exceptional resistance to extreme climatic changes. The choice of wood used in the construction industry depends on several factors, such as price, distribution according to the region, durability, environmental impact, etc. In addition, it is crucial to consider the specific structural elements and the aesthetic characteristics of the housing or facilities being built. The most widely used species in the construction industry are coniferous species, of which Scots pine (*Pinus sylvestris* L.) accounts for a significant share. The wood of this species is mainly used to produce glued-laminated timber (GLT), cross-laminated timber (CLT), partition walls, doors, windows, flooring, etc. The reason for this is that Scots pine is distinguished by a beautiful texture, high resistance to mechanical loads, relatively low density; furthermore, it is easy to process and economically advantageous (Mederski *et al.,* 2015; Mclean, 2019; Burawska-Kupniewska *et al.,* 2020). Wood from the *Quercus* genus or other hard deciduous or tropical species is preferred in constructing heavy-duty structures where greater durability is required.

On the other hand, the aesthetic appearance of wood as a natural material leads to a feeling of high comfort and tranquillity for the inhabitants. Along with all the advantages of wood, there are also numerous disadvantages, primarily related to its anatomical structure, which leads to significant anisotropy. When using wood in load-bearing constructions, these disadvantages have a significant negative impact on their mechanical performance. Modern technologies allow many wood disadvantages to be overcome by removing areas of concentrated influence and subsequent bonding using synthetic adhesives (Akiner *et al.,* 2022; Bayat, 2023).

2 TYPES OF SYNTHETIC ADHESIVES IN WOODWORKING, FURNITURE AND CONSTRUCTION INDUSTRY
2. VRSTE SINTETIČKIH LJEPILA U DRVOPRERAĐIVAČKOJ I GRAĐEVNOJ INDUSTRIJI TE INDUSTRIJI NAMJEŠTAJA

The woodworking industry is the largest consumer of adhesives worldwide, and 70 % of the total volume of adhesives produced is applied in this sphere (Sandberg, 2016).

Adhesives used for producing engineered wood must be sufficiently stable in water, resistant to fungal attack and have high shear strength. Synthetic-based adhesives that meet the above requirements are primarily used in manufacturing this type of product. These resins are toxic to one degree or another due to the release of formaldehyde emissions into the atmosphere. For this reason, depending on the application of the glued wood materials, the use of the appropriate type of adhesive is recommended. The reduction of the free formaldehyde contained in the bonded products is an essential necessity, as it largely determines the environmental friendliness of the final product. According to European standard EN 717-1 (CEN 2004) for emission class E1, this indicator should be ≤ 0.124 mg/m^3 air (Sung *et al.,* 2012; Gonçalves *et al.,* 2021; Chrobak *et al.,* 2022).

The correct choice of the type and composition of the adhesive determines not only the strength and durability of the adhesive joint, but also the price of the products manufactured. Therefore, the choice of adhesive in a specific case must be consistent not only with the factors to which the structure will be exposed but also ensure low cost and high operational strength (Pizzi, 2003).

In this case, the adhesives join the wood elements in a bond that resembles or is close to the bond between the wood fibres in their natural state. Wood materials obtained in this way should not be inferior in terms of physical and mechanical parameters to natural wood of the same dimensions (Ülker, 2016).

The adhesive used to obtain EWPs in the constructions must ensure the structure durability for a long period. In most cases, the operation of these structures takes place outdoors under the influence of humidity and/or dryness of the air, as a result of which the wood swells or dries up. These constructions are exposed to significant changes in temperature fluctuations and the adhesives used for their production must withstand these changes (Senft, 2002). The so-called predicted assessment of the resistance of these joints also plays an essential role in solving problems of engineered wood durability.

This assessment provides information about the lifespan of the structures built. It further shows that the obtained values for the durability of the bonded products meet the requirements, and the possibilities for improving the connections and adhesives used (Hänsel *et al.,* 2021).

In the given case, the durability of the glued wood means its ability to store the adhesion and cohesion bonds over a long period until the minimum permissible values are reached or until it is destroyed.

2.1 Classification of synthetic wood adhesives
2.1. Klasifikacija sintetičkih ljepila za drvo

Synthetic adhesives used in the woodworking, furniture and construction industry can be classified based on several criteria (Dunky and Pizzi, 2002; Ormondroyd, 2015). Depending on the production method, adhesives are divided into polymerization and polycondensation types. In polymerization adhesives, the molecules of the monomer are linked to form macromolecules, resulting in a polymer while maintaining the chemical composition of the compound. The release of a low-molecular product does not accompany the polymerization process. Polymerization adhesives include polyvinyl acetate, polyvinyl chloride, polyacrylic, etc.

In the second case, polycondensation involves bonding two or more monomers into a higher molecular weight product, during which low molecular weight by-products, such as water, ammonia, hydrogen chloride, etc., are released. Polycondensation adhesives include phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, etc.

Depending on the water resistance of the adhesive joints, adhesives are classified as follows: non-water-resistant (polyvinyl alcohol and polyvinyl acetate adhesives), medium water resistant (urea-formaldehyde adhesives), and high-water resistant (phenol-formaldehyde, melamine-formaldehyde, and resorcinol-formaldehyde adhesives).

According to their intended use, adhesives are divided into two groups:

- Structural: They find application for products and structures subjected to high mechanical stress, such as multi-layer glued load-bearing beams, columns, arches, solid wood panels, etc. Adhesives for the manufacturing of structural glued wood products must comply with the relevant European standards: EN 301 (CEN 2023), EN 15425 (CEN 2023) and EN 16254 (CEN 2023), as well as the harmonized standards defined by the European Union's Construction Products Regulation (CPR) to assess the performance of construction products: EN 14080 (CEN 2013), EN 14374 (CEN 2004) and EN 1995-1-1 (CEN 2004).
- Non-structural: In these cases, the adhesive joint is not designed to withstand significant loads. Therefore, these adhesives are mainly used in the furniture industry, such as furniture, decorative elements, packaging, toys, kitchen utensils, etc. The main standards that non-structural adhesives must comply with are ISO 19209 (ISO 2017), EN 12765 (CEN 2016) and EN 17619 (CEN 2021).

Synthetic adhesives can be categorized into liquid, paste-like, powdery, and sheet forms based on their appearance before use.

Depending on the curing mechanism, adhesives can be divided into thermoplastic and thermosetting. Thermoplastics are polymers with a linear structure that can be melted when heated in a solid state and can cure upon cooling. This process is reversible. In contrast, thermosetting polymers have a two-or three-dimensional cross-linked structure that becomes solid, infusible, and insoluble upon heating. In this case, the process is irreversible.

The most widely used adhesives in the woodworking industry are thermosetting polymeric condensation synthetic resins, which form adhesive joints with very good physical and mechanical properties.

2.2 Most commonly used adhesives for the production of EWPs
2.2. Najčešće upotrebljavana ljepila za proizvodnju kompozitnog drva

The most commonly applied thermosetting resins for the manufacturing of EWPs are amino resins, phenolic resins, isocyanates, and polyurethane adhesives. The conditions for their synthesis and curing are of particular importance. Upon heating, this group of polymers transforms into cross-linked solid materials that cannot be further processed. Cross-linking occurs through the formation of a significant number of covalent bonds, creating infusible and insoluble products.

A deep understanding of these processes will enable the optimization of the curing process by adding various substances. This, in turn, will create conditions to reduce the impact of harmful emissions, and enhance the properties of adhesive joints (Mo *et al.,* 2015; Liu *et al.,* 2018).

Common thermoplastic wood adhesives applied for the production of EWPs are polyvinyl acetate emulsions.

Based on this knowledge, opportunities for the production of environmentally friendly, reliable, and durable products will be created (Dorieh *et al.,* 2022a)

2.2.1 Phenol-formaldehyde (PF) adhesives
2.2.1. Fenol-formaldehidna (PF) ljepila

Phenol-formaldehyde oligomers are obtained by interacting with synthetic phenol or its derivatives (cresol, xylenol, and resorcinol) with formaldehyde (Berdnikova *et al.,* 2021). Phenol is condensed with formaldehyde in an alkaline medium with an excess of formaldehyde to obtain resole (thermosetting) oligomers. The ratio of phenol to formaldehyde used in resoles is between 1:1.5 and 1:2.2. Hydroxides of alkali (potassium, sodium) and alkaline earth metals (barium, calcium) as catalysts in the synthesis of resoles are applied. The reaction for the production of resoles primarily depends on changes in the reagent molar ratio, the reaction temperature and duration, as well as the type and amount of catalyst.

Resole PF resins are a mixture of linear and branched oligomers containing a large number of hydroxymethyl groups (–CH_2OH), which are capable of further transformations. Their curing is carried out by heating (130-150 °C) or in the presence of acid catalysts (benzenesulfonic acid, phosphoric acid). Upon heating, resole transforms into resitol and resite. These stages are accompanied by an increase in the molecular weight of the polymer and the formation of a three-dimensional cross-linked structure.

Novolac (thermoplastic) oligomers are synthesized in the presence of acid catalysts (such as hydrochloric acid, sulfuric acid, or oxalic acid) with excess phenol. As a result, novolac PF oligomers with a predominantly linear structure are formed and phenolic cores are connected by methylene bridges. Novolac resins are solid and soluble. Their curing occurs using urotropine, and less frequently, paraformaldehyde at temperatures between 150-180 °C. The production of PF resins is schematically shown in Figure 1 (Atta-Obeng, 2011).

These adhesives are characterized by very good adhesion to various materials, and high cohesive strength. Other significant advantages of these adhesives include the availability of raw materials and ease of synthesis (Berdnikova *et al*., 2021). The formed adhesive joint is distinguished by high bonding strength, heat resistance (up to 300-400 °C), water resistance (both in cold and hot water), and biological resistance.

One of the disadvantages of PF adhesives is their red-brown colour, which leads to staining of the adhesive joint. Fragile adhesive joints with high hardness are formed, making machining difficult and leading to the wear of the cutting tools. The significant disadvantage of this type of adhesive is the toxicity of phenol and formaldehyde, as well as the formaldehyde emissions. For this reason, bonding products that are used indoors are not recommended. The toxicity problem can be solved in various ways, one of which is the replacement of PFR with UFR or MFR resins.

Several authors have conducted studies on using various compounds known as formaldehyde scavengers that capture the released formaldehyde (Kristak *et al.,* 2022). Ramdugwar *et al.* (2022) investigated the addition of sodium sulphite and sodium metabisulfite

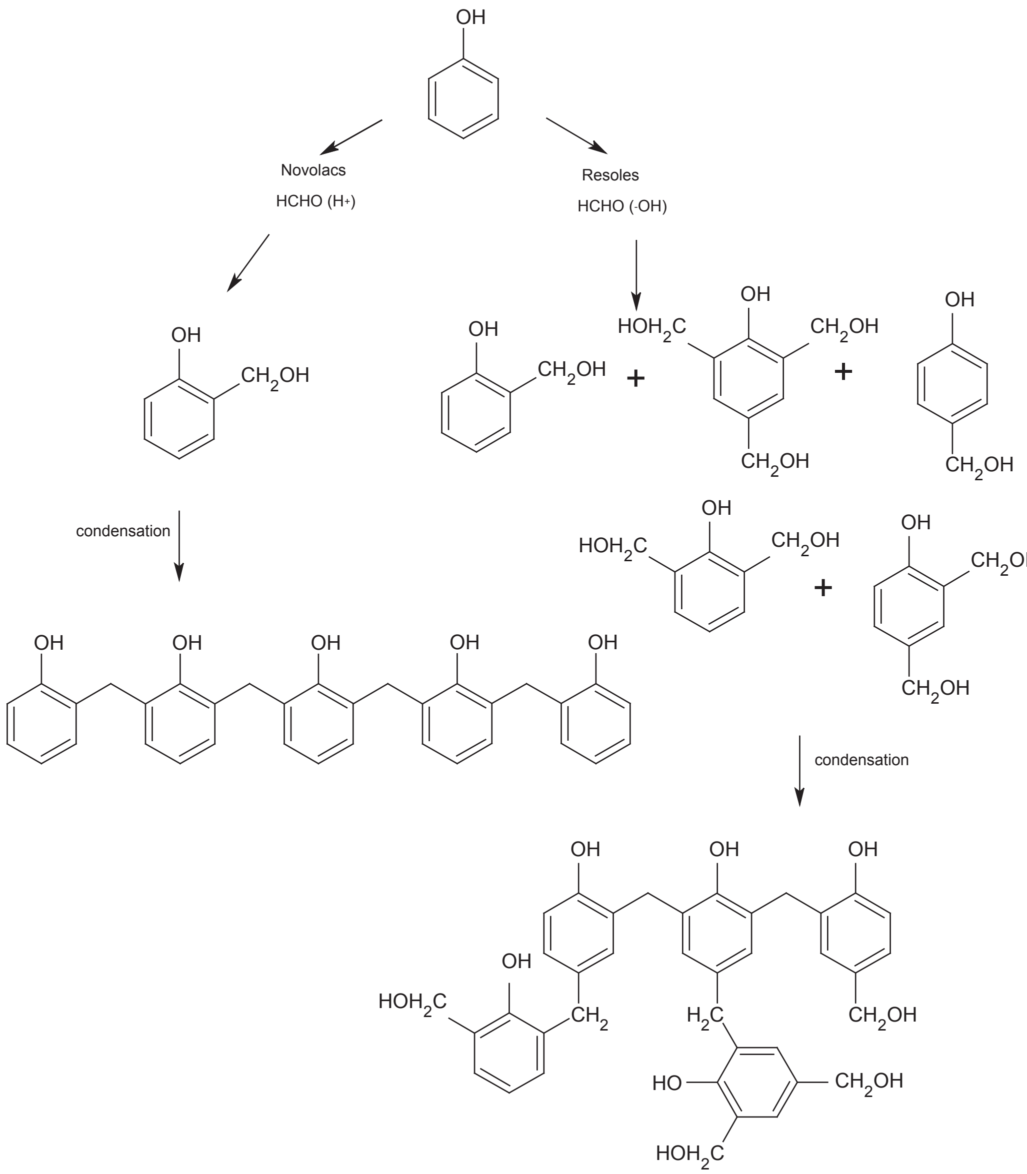


Figure 1 Synthesis of novolac and resole PF resin (Atta-Obeng, 2011)
Slika 1. Sinteza novolaka i rezol PF smole (Atta-Obeng, 2011.)

to phenolic resin to reduce formaldehyde emission. The authors found that these two substances significantly decrease formaldehyde content without affecting adhesive performance. Other authors considered the incorporation of tannin from the bark of *Acacia mangium* into the formulation of low molecular weight PF resin to absorb free formaldehyde. The resulting modified adhesive meets the standard requirements, and tannin can be used as a formaldehyde scavenger without compromising the strength of the adhesive joints (Hoong *et al.,* 2010).

2.2.2 Phenol-resorcinol-formaldehyde (PRF) and resorcinol-formaldehyde (RF) adhesives
2.2.2. Fenol-rezorcinol-formaldehidna (PRF) i rezorcinol-formaldehidna (RF) ljepila

Phenol-resorcinol-formaldehyde (PRF) adhesives are obtained by introducing resorcinol during the synthesis of PF resin. Substituting phenol with resorcinol leads to resorcinol-formaldehyde (RF) resin formation. These two types of adhesives are characterized by a significant reduction in curing time compared to PF resin. The chemical reactions associated with producing and curing of PRF and RF resins are similar to those for PF resin (Dunky and Pizzi, 2002; Durairaj, 2005; Wibowo and Park, 2024). Resorcinol is responsible for the accelerated curing at room temperature, both in the composition of RF and PRF resins. Pure RF oligomers are typically produced at a molar ratio of formaldehyde to resorcinol of less than one, in a neutral or slightly alkaline medium.

PRF adhesives are commonly prepared by reacting phenol with formaldehyde, resulting in the formation of a PF resole polymer with a predominantly linear structure. In a subsequent reaction, resorcinol in excess that reacts with the –CH2OH groups is added to produce the PRF polymers.

RF adhesives can be used for hot (150-180 °C) and cold gluing. Curing at room temperature occurs very rapidly, which leads to the development of stresses in the adhesive joint and to its faster failure. Therefore, it is preferred to operate at lower temperatures. In contrast to PF resins, these adhesives cure at room temperature in an acidic, neutral, or slightly alkaline medium.

RF adhesives form adhesive joints characterized by excellent adhesion, high water, heat, atmospheric and chemical resistance, and n on-toxicity. A key disadvantage of these adhesives is the high cost of resorcinol. Therefore, they are used in combination with PF resins. Another approach to reducing resorcinol content is to modify PF resins by grafting resorcinol onto the active hydroxymethyl groups of low condensation resoles obtained from the reaction of phenol with formaldehyde (Dunky and Pizzi, 2002).

2.2.3 Urea-formaldehyde (UF) adhesives
2.2.3. Urea-formaldehidna (UF) ljepila

The synthesis of urea-formaldehyde (UF) resin occurs in two stages (Kloeser *et al.,* 2007). The first stage involves the interaction between urea and formaldehyde in a weakly basic or neutral medium, primarily resulting in the formation of mono- and dihydroxymethylurea (Figure 2). In the second stage, condensation of the obtained products takes place, leading to the formation of low-molecular-weight polymers. At acidic pH, the molecular weight of the condensation products increases due to the formation of ether and methylene links.

UF adhesives are two-component adhesives and cure either upon heating or at room temperature. For cold curing, diluted solutions of inorganic acids (phosphoric, sulfuric) or organic acids (oxalic, phthalic) are used as hardeners. The quantitative proportion of the hardener is up to 5 % relative to the weight of dry resin.

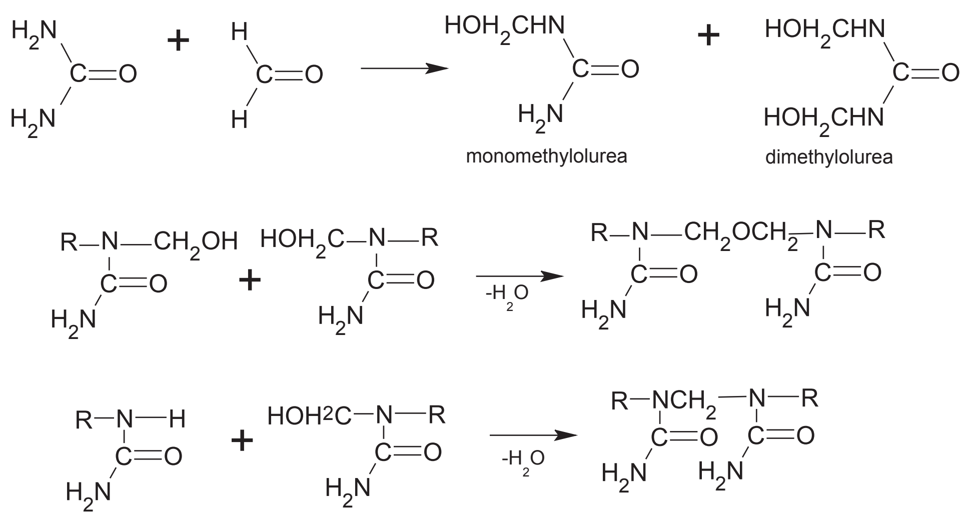


Figure 2 Condensation reactions for obtaining urea-formaldehyde resins
Slika 2. Reakcije kondenzacije za dobivanje urea-formaldehidnih smola

Salts of strong acids (ammonium chloride, ammonium sulphate, ammonium nitrate) in the form of 20 % solutions or as powder are employed for hot bonding. Their quantity is typically around 1 % relative to the weight of dry resin.

UF adhesives are inexpensive and readily available. They are characterized by good adhesion to wood, light resistance, and colourlessness. The adhesive joints have moderate atmospheric resistance and are resistant to microorganisms. These adhesives are easy to use and cure quickly, especially at high temperatures. UF adhesives exhibit good strength characteristics (Ülker, 2016; Antov *et al.,* 2021).

Despite the listed advantages, these adhesives also have some disadvantages. They are very sensitive to temperature and pH of the environment. They exhibit moderate water resistance and have a short shelf life. The adhesive joints are rigid and brittle, which can generate internal stress and lead to crack formation during curing. In addition, a serious drawback is the emission of formaldehyde. This can be controlled by an appropriate F/U molar ratio or by adding substances to the adhesive mixture that can capture the free formaldehyde (Pizzi, 2003; Maslosh *et al.,* 2005; Bilgin and Colakoglu, 2021).

2.2.4 Melamine-formaldehyde (MF) and melamine-urea-formaldehyde (MUF) adhesives

2.2.4. Melamin-formaldehidna (MF) i melamin-urea-formaldehidna (MUF) ljepila

Melamine-formaldehyde (MF) oligomers are obtained through the polycondensation of melamine (1,3,5-triamino-2,4,6-triazine) and formaldehyde in two stages, as illustrated in Figure 3 (Merline *et al.,* 2013; Dorieh *et al.,* 2022b). In the first stage, the aldehyde reacts with the amino groups, leading to the generation of hydroxymethyl compounds (hydroxymethylation step). A neutral or slightly alkaline medium (pH 7-8.5) favours this reaction. The addition of the first three molecules of formaldehyde occurs rapidly, forming trihydroxymethylmelamine (Figure 3). In the condensation stage, the hydroxymethyl compounds can react with each other, leading to the formation of methylene and methylene ether linkages. The former predominates at pH between 7 and 8, while the latter - at pH above 9. The curing of MF resins occurs in the presence of an acidic catalyst at elevated temperatures (130-150 °C), but it can also proceed in a neutral or slightly alkaline medium.

The structure of the obtained MF adhesives depends on the synthesis conditions, namely: mole ratios of the raw materials, temperature, and pH.

Due to the high cost of MF adhesives, the production and use of so-called melamine-urea-formaldehyde (MUF) resins are becoming more prevalent. These thermosetting resins are obtained by the interaction of urea, melamine and formaldehyde. Relative mass proportions of melamine to urea typically range from 50:50 to 30:70 (Pizzi and Ibeh, 2014). The properties of these MUF resins are influenced by the synthesis method, the order of component addition, molar ratios, and melamine content (Tohmura *et al.,* 2001). The latter significantly affects the solid content, gelation time, and viscosity, as well as the chemical properties of the resin.

MUF resins outperform UF resins because they offer several advantages, such as better water resistance, colourlessness, lower price, and fewer formaldehyde emissions (Kim and Park, 2021).

One of the most valuable properties of MF adhesives is their high water resistance, not only in cold but also in boiling water. In this regard, they do not fall short of PF resins. Other significant advantages of these adhesives include their non-hazardous nature and excellent bonding strength. The adhesive joints are colourless and more moisture and heat resistant than UF adhesives (Dorieh *et al.,* 2022b).

A disadvantage of MF adhesives is their high cost, which limits their application. Therefore, MUF adhesives combine the good adhesion properties of melamine adhesives with the lower cost of urea adhesives (Li *et al.*, 2023). Another drawback of MF adhesives is limited storage stability due to the presence of many imino and hydroxymethyl groups (Lan *et al.,* 2019).

2.2.5 Polyurethane and polyisocyanate adhesives

2.2.5. Poliuretanska i poliizocijanatna ljepila

Polyurethane-based adhesives have extensive applications in the woodworking and furniture industry (Dimitrov *et al.,* 2017). The starting components for the synthesis of polyurethanes (PU) are polyisocyanates-methylene diphenyl diisocyanate (MDI) or toluene diisocyanate (TDI) and polyols (Akindoyo *et al.,* 2016; Kemona and Piotrowska, 2020). The most crucial unit in the composition of PU is the urethane linkage (–NH–COO–), which is formed by the reaction of isocyanate group with hydroxyl group from the polyols (Figure 4).

Isocyanates used in the production of wood composites vary depending on the type of wood composite and the required physical and mechanical properties. Organic isocyanates, typically polymeric methylene diphenyl diisocyanate (pMDI), have been used as adhesives since the early 1970s. The synthesis of pMDI starts with the condensation of aniline with formaldehyde in an acidic solution (Conner, 2001). As a result, a complex mixture of isomeric diamines and oligomeric polyamines is formed. The pMDI is produced by the phosgenation of aniline-formaldehyde condensates.

The adhesive properties of pMDI are based on the reactivity of isocyanate groups, which react with com-

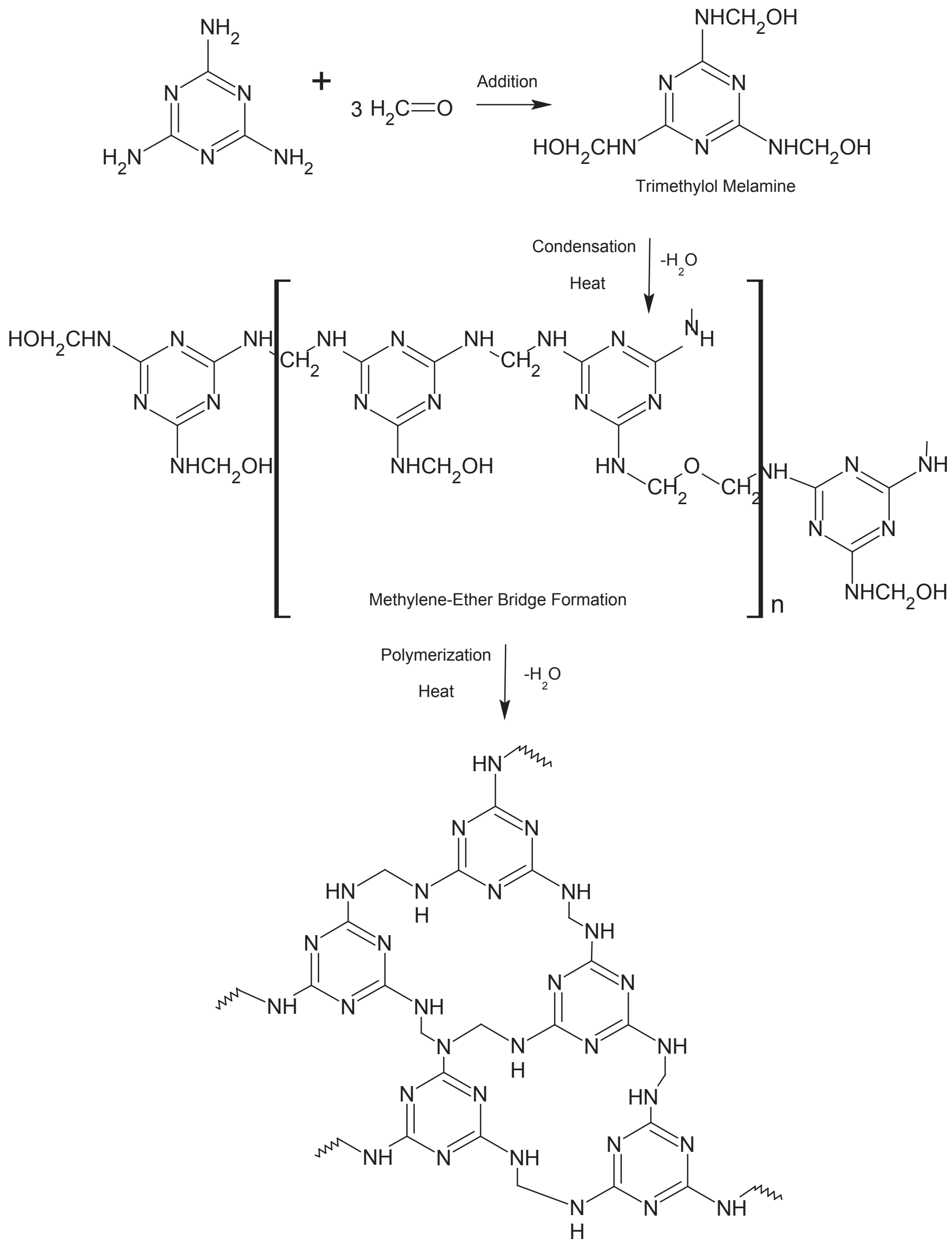


Figure 3 General reactions to form MF resin
Slika 3. Opće reakcije dobivanja MF smole

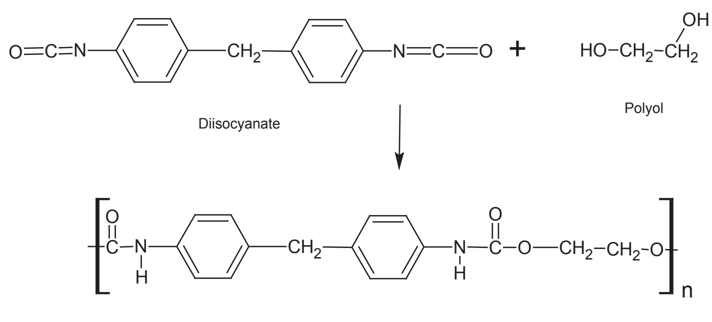


Figure 4 Reaction example for polyurethane synthesis
Slika 4. Primjer reakcije sinteze poliuretana

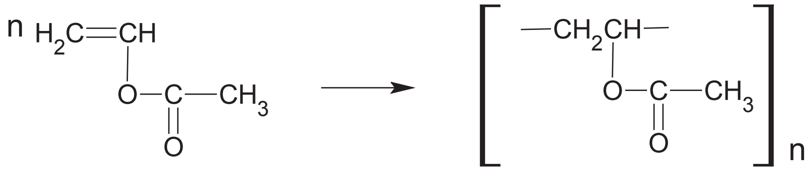


Figure 5 Polymerization reaction to produce polyvinyl acetate
Slika 5. Reakcija polimerizacije za dobivanje polivinil-acetata

pounds containing active hydrogen, such as water, alcohols, and amines. The reaction rate increases with heat. pMDI is an effective bonding agent for wood at increased moisture content, as it reacts with water to produce polyurea (Kloeser *et al.,* 2007). Covalent bonds may theoretically be formed between hydroxyl groups in the wood and the isocyanate, facilitating the anchoring of polyurea and filling the gaps between wood pieces.

PU adhesives are noted for their high adhesion to various materials, including wood, due to the presence of polar –N=C=O groups. They have several advantages such as universality; and can cure at room temperature, under heat for a short period, and at low pressure. Durability, atmospheric resistance, as well as very good strength indicators characterize the adhesive joints (Shirmohammadli *et al.,* 2023).

The primary disadvantage of PU adhesives is their toxicity due to the presence of isocyanates. It can be reduced by using blocked isocyanates (Wirts *et al.,* 2003).

Polyisocyanate adhesives, primarily based on pMDI, have several advantages. They exhibit excellent adhesion and cohesion, high reactivity, and effective bonding, forming connections even in high moisture content. The resulting adhesive joint is characterized by excellent hardness and plasticity, along with biological and chemical resistance (Kawalerczyk *et al.,* 2023). There are no formaldehyde emissions, which negatively affect the production process and are associated with additional costs.

Along with these advantages, pMDIs also have some disadvantages, namely their high cost and the tendency to bond with other materials, such as press tops, which limits their use for gluing in the surface layers of wood composites. Another disadvantage is the toxicity of isocyanates; therefore, measures to prevent the risk of diseases when using these substances are needed (Kloeser *et al.,* 2007; Frihart, 2012).

2.2.6 Polyvinyl acetate (PVAc) adhesives
2.2.6. Polivinilacetatno (PVAC) ljepilo

Polyvinyl acetate (PVAc) adhesives are thermoplastic, polymerization adhesives based on polyvinyl acetate, which is obtained by polymerization of vinyl acetate according to the following scheme (Figure 5), (Frihart, 2012):

The raw materials for the production of vinyl acetate are acetylene and acetic acid, which interact in the following reaction (Figure 6):

Depending on the method of polymerization, polyvinyl acetate can be obtained either as a solution in an organic solvent and a water emulsion or as a solid that melts upon heating. The PVAc emulsion finds the greatest application in wood bonding, specifically at 65 °C (Gadhave and Dhawale, 2022). Hydrogen peroxide is the initiator of the reaction, polyvinyl alcohol is an emulsifier, and formic acid acts as the pH regulator.

Plasticized and non-plasticized PVAc emulsions are white liquids with varying viscosities. Its pH is acidic due to the presence of acetic acid. Plasticisers, particularly dibutyl phthalate, can be added to the polyvinyl acetate emulsion. Plasticized and non-plasticized PVAc emulsions can bond wood quickly, either upon heating or without heating.

Wood bonding occurs because of a physical process in which the solvent (water) penetrates the depths of the wood. The polymer film remains leaving it in the adhesive layer and forming an elastic adhesive joint (Bomba *et al.,* 2014).

Using these adhesives in the furniture and construction industry guarantees technological efficiency. Therefore, depending on the duration of a specific operation, their polymerization and polycondensation can be accelerated by adding a hardener or rising the temperature. This is accompanied by an increase in the bond number between molecules and the formation of a spatial structure, enhancing the adhesive properties of specific resins. Based on the presented interactions between the molecules during the curing process, a particular type of binder can be selected to ensure the desired performance characteristics of the final products.

Unfortunately, the curing of these adhesives that guarantee high atmospheric resistance and performance under severe weather conditions, is associated with releasing large amounts of formaldehyde emissions. For

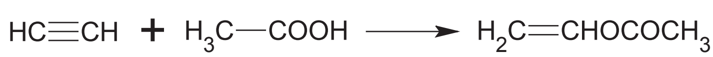


Figure 6 Reaction to produce vinyl acetate
Slika 6. Reakcija dobivanja vinil-acetata

this reason, the addition of formaldehyde scavengers aims to limit this negative factor as much as possible.

PVAc has long been among the cheapest adhesives used in the woodworking industry. They are characterized by good adhesion to various materials, absence of internal stress in the adhesive joint, complete safety, light resistance, storage stability, elasticity of the adhesive joint, and simplicity in bonding (Gadhave and Dhawale, 2022; Aydemir, 2014).

The disadvantages of PVAc adhesives are expressed in their thermoplasticity, low heat and water resistance. These bonding compounds undergo modification to improve their physical and mechanical properties (Kaboorani and Riedl, 2011; Morsi *et al.,* 2024).

3 TYPES OF EWPs INTENDED FOR CONSTRUCTION INDUSTRY
3. VRSTE KOMPOZITNOG DRVA U GRAĐEVNOJ INDUSTRIJI

In recent decades, it has been observed that wood consumption has been increasing not only in the furniture industry, but also progressively, in the construction industry (FAO, 2014; FAO, 2020). There has been heightened demand for and manufacturing of a wide variety of products, including glued laminated timber, composite panel materials, solid wood materials, and glued solid wood products. These items are mainly used in the construction of housing, buildings and facilities, as well as in the automotive, railcar and aircraft industry.

Composite laminated materials, commonly called EWPs, cover a wide range of assortments. Depending on the intended application of the final products, these items are formed by bonding solid wood components without defects, or by gluing veneer sheets, veneer pieces, large wood particles (wood chips), etc. (Bayat, 2023; Yadav and Kumar, 2021).

Rapid development of the construction industry necessitates an increased use of wood-based structural elements to build a significant portion of homes, buildings, and facilities. A substantial part of this includes multi-layered glue-laminated solid wood beams (GLT), single-layer glue-laminated wood beams (KVH structural timber), glued laminated panels with mutually perpendicular fibre orientation (CLT), and double T-beams. There is also a growing utilization of structural materials based on veneer sheets and pieces (LVL, PSL, SCL, and OSB).

Table 1 presents some of the most commonly used EWPs in the construction industry.

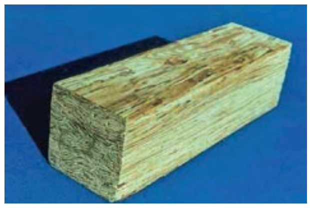
4 APPLICATION OF EWPs
4. PRIMJENA KOMPOZITNOG DRVA

The fields of application for the materials described above are quite diverse. These products are pri-

Table 1 Classification of composite materials (APA Wood)
Tablica 1. Podjela kompozitnih materijala (APA Wood)

Types of engineered wood (EWPs) *Vrste kompozitnog drva (EWP)*	**Definition** / *Definicija*	**Image** / *Slika**
GLT/Glued-laminated timber (glulam) *lijepljeno lamelirano drvo (glulam)*	Structural materials (beams) produced by layers of dimensional lumber bonded together with structural adhesives *konstrukcijski materijal (grede) proizveden od slojeva dimenzioniranog drva spojenih konstrukcijskim ljepilima*	
KVH structural timber *KVH konstrukcijsko drvo*	Structural materials (single-layer beams) produced by longitudinal finger-jointed splicing corresponding to strength class C24 *konstrukcijski materijal (jednoslojne grede) proizveden uzdužnim spajanjem zupcima koji odgovaraju klasi čvrstoće C24*	
CLT/Cross- laminated timber *CLT / unakrsno lamelirano drvo*	Panels of glued lamellae with mutually perpendicular orientation of the fibre direction *ploče od lijepljenih lamela s međusobno okomitom orijentacijom smjera vlakana*	
I-joists, I-beams *I-grede*	Double T- beams of OSB (or plywood) and solid wood *dvostruke T-grede od OSB-a (ili furnirske ploče) i masivnog drva*	

Table 1 Continue
Tablica 1. Nastavak

Types of engineered wood (EWPs) *Vrste kompozitnog drva (EWP)*	**Definition** / *Definicija*	**Image** / *Slika**
LVL/Laminated veneer lumber *LVL / lamelirano furnirsko drvo*	Materials (beams) obtained by pressing several layers of veneer with configuration in the longitudinal direction *materijal (grede) dobiven prešanjem nekoliko slojeva furnira s konfiguracijom u uzdužnom smjeru*	
SCL/Structural composite lumber *SCL / konstrukcijsko kompozitno drvo*	Materials obtained by bonding veneer pieces and wood particles under high pressure *materijal dobiven lijepljenjem komada furnira i drvnih čestica pod visokim tlakom*	
PSL/Parallel strand lumber *PSL / građevno drvo od traka furnira*	Materials produced from veneers clipped into long strands laid in parallel formation and bonded together with an adhesive *materijal proizveden od furnira izrezanih u duge trake položene paralelno i spojene ljepilom*	
OSL/Oriented strand lumber *OSL / građa s orijentiranim iverjem*	Materials obtained by gluing wood strand elements with wood fibres primarily oriented along the length of the product under high pressure *materijal dobiven lijepljenjem drvnog iverja pod visokim tlakom s vlaknima pretežito orijentiranima duž duljine proizvoda*	
OSB /Oriented strand board, waferboard *OSB / ploča s orijentiranim iverjem*	Boards of oriented large-sized wood particles *ploče od orijentiranih drvnih čestica velikih dimenzija*	

*The sources from which the images were taken are indicated in the references (83-91).
**Izvori iz kojih su slike preuzete navedeni su u popisu literature (83. – 91.).*

marily used in residential and public buildings, sports facilities, bridges, awnings, etc. Therefore, in the construction industry, EWPs are mainly categorized into two groups: load-bearing and enclosing structures.

Enclosing structures most commonly include products such as plywood, OSB, and in recent years, there has been a rapid increase in the consumption of CLT. The choice of binder depends on the environment in which it will be used. The most frequently used adhesives for manufacturing these products are PF (softwood plywood and OSB), pMDI (for OSB), UF (hardwood plywood), and PVA (Aydin *et al.,* 2006; Ferreira *et al.*, 2022; Sulastiningsih *et al.,* 2024; Ibrahim and Febrianto, 2013; Chanda *et al.,* 2022). The most suitable adhesives used for CLT production are melamine, PRF, and resorcinol-based resins, as well as one-component PUR adhesives (Mohd Yusof *et al.,* 2019; Miyazaki *et al.,* 2024).

Load-bearing structures include beams, arches, frames, trusses, domes, spatial structures, and others. One of the most commonly used materials in constructing these facilities is glued laminated timber (GLT).

Glued laminated beams of the GLT type have a low volumetric mass, high strength properties, and significant durability under various conditions, which is generally measured in decades. Depending on the operating environment, special attention is paid both to the type of wood used to form the structural package, and to the adhesive used for their preparation. Overall, GLT products provide four general-use categories, which are specified in ANSI A190.1-2012 (2013).

Framing Elements: This framing type is a common choice for residential construction. This GLT class is recommended only for hidden locations.

Industrial: These industrial-grade GLT are used in the construction of structures where aesthetic appearance is not essential. Their application is primarily seen in elements that are not visible to the public, as these materials may exhibit certain imperfections in the wood, such as joints, cavities, holes, etc.

Architectural: When GLT is to be used as facade material or external element of buildings and structures, the architectural class offers high product quality, free of voids and defects in the wood, and with a very good aesthetic appearance.

Premium (very high class, made to order): This GLT class is produced only to special orders and is typically used in areas where high concentrations of people are expected. The Premium class offers wood with smooth surfaces and fine finishes, resulting in a high-quality final product.

The most commonly used adhesives for GLT production are PRF type, MUF, one-component PUR and in some cases, PVAc adhesives (Fiorelli and Dias, 2006; Derkowski *et al.,* 2022; Ayanleye *et al.,* 2023; Kytka *et al.,* 2024). The latter are used only when the structural elements are not exposed to severe atmospheric conditions, such as drastic temperature changes and high humidity.

Another type of EWP for constructing load-bearing structures is a material created by bonding veneer sheets or pieces. These typically include products such as LVL, SCL, PSL, OSL, etc. Since the defects in the wood used to construct these products and the bonding of veneer pieces are clearly visible, these products are primarily applied in the construction of hidden structures.

The most commonly used adhesives for manufacturing LVL, SCL, PSL, and OSL are PF, MF, MUF, and pMDI (Ferraz *et al.,* 2009; Kurt and Çavuş, 2011; Kurt and Cil, 2012; Sun *et al.,* 2021; Malanit *et al.,* 2011).

4 CONCLUSIONS
4. ZAKLJUČAK

This review focuses on the most common synthetic adhesives applied in the manufacturing of some EWPs. The type of bonding agents not only guarantees high resistance of the final products to adverse weather conditions but may also be associated with formaldehyde emissions. Therefore, the choice of adhesive must be consistent with the operating conditions.

The adhesives based on melamine, phenol and resorcinol considered in this study are particularly preferred due to their high moisture resistance, temperature fluctuations and high durability under structural loads. It should be noted, however, that their significantly high price makes the final product more expensive. UF adhesives are particularly preferred in industry due to their high cost-efficiency and good adhesion properties, but they have low water resistance. Other types of adhesives such as polyurethane and isocyanate are known for their excellent mechanical properties and water resistance. Their use guarantees very strong adhesive joints, as well as great durability of the elements. It should be noted that some of the adhesives described so far release free formaldehyde, the amount of which depends on their synthesis.

High water resistance does not characterize PVAc adhesives, but they have several other advantages such as elasticity, ease of processing, and environmental friendliness. As a result, they are increasingly used in both the furniture and construction industries.

The future of adhesives for EWPs is focused on sustainability, performance, and innovative applications. Market growth is projected, driven by increasing urbanization, demand for sustainable building materials, and advancements in adhesive technology. All these factors contribute to a growing interest in developing high-performance adhesives for use in demanding environments and create opportunities for optimizing manufacturing processes.

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