Analysis of Future Prospects and Opportunities for Wood Adhesives: A Review*

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Abstract

This paper addresses strengths, weaknesses, opportunities, and threats of the wood adhesives industry as discussed at the International Conference on Wood Adhesives in May 2022. The authors have organized the points made during the discussion and added further facts, assumptions, and conclusions to provide context and perspective, even surpassing the outcome of the discussion. The biggest themes of the discussion were the unprecedented opportunity for adhesives to enable forest products to supply society's surging demand for renewable materials and the challenges in meeting those demands. We see excellent opportunities for wood-based panels and with this, for wood adhesives. The abundant challenges to bio-based adhesives for wood products are highlighted by the large amount of research and commercial effort compared with the small volumes of bio-based adhesives in use. Other threats to the adhesive and bonded products industries include aversion to any chemicals (even stable adhesives), and lack of experienced work force. Wood adhesives underwent significant changes in the past decades, mainly focused on reducing emissions during panel use. Wood use in construction will be boosted by efforts to fulfil the European Green Deal, as implemented in the New European Bauhaus and European Renovation Wave.

Wood products supply a significant fraction of the materials we use as a society—1.3 billion m^3 of industrial wood was harvested in 2020, resulting, among other products, in 368 million m^3 of panel products (Food and Agriculture Organization of the United Nations [UN FAO] 2022). All panels and many other wood products depend on adhesives for their performance, resulting in an adhesive demand we estimate at up to 18M (million) tons/yr. This number was calculated based on the global production of the various types of wood-based panels with their characteristics concerning types of adhesives and amounts used in the production of the panels. This was mainly based on long-term experience in chemical- and wood-based panels industry. The volumes of wood-based panels were taken from official statistics, such as (UN FAO 2022), FAO Yearbook (UN FAO 2018), or European Panel Federation Annual Report (EPF 2022). We estimate ~85 percent of adhesive volume is urea-formaldehyde (UF, typically 65% solids by weight, often with small portions of melamine), followed by phenol-formaldehyde (PF), melamine-formaldehyde (MF), and polymeric methylene diisocyanate (pMDI; estimation based on long-term personal experience of the one of the authors, M.D., in chemical and wood-based panels industry). These adhesives are used alone or in combination for the production of wood-based panels, i.e., particleboard (PB), medium/high density fiberboard (MDF/HDF), oriented strand board (OSB), and plywood. Polyurethane (PUR), PF, phenol-resorcinol-formaldehyde (PRF), emulsion polymer isocyanate (EPI), and polyvinyl acetate (PVAc), as well as a wide variety of smaller chemistries are used for solid wood lamination, construction beams, coating of boards with veneers or finish foils, or special applications.

This paper captures the thoughts of leaders of the wood adhesives industry as discussed during the International

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Conference on Wood Adhesives in May 2022 in Portland, Oregon. We organized the issues discussed at the Conference and the paper here around the four headings of Strength, Weakness, Opportunities, and Threats (SWOT) relevant to the wood adhesive industry, but not a proper SWOT analysis. In addition to reflecting the comments and discussion points of the group, the authors have added context and references, which will hopefully make the content useful to a broader audience. Panel products consume such a large fraction of all wood adhesives, so panel products were the focus of much attention at the conference attendees and this document.

Comparing a similar panel discussion at the International Conference on Wood Adhesives 2017 (Kamke 2018), the discussion of 2022 covered many of the same themes. The notable changes were the intensity of effort in bio-based adhesives, while at the same time regrettably acknowledging that bio-based adhesives are not capturing market at a rate sufficient to meet many goals (Dunky 2021, 2022). This reflects the difficulty in bringing new technical solutions to a market dominated by low cost, well-established, highly sophisticated, optimized, and well-understood incumbent technologies.

One thing that has definitely receded has been the concern with formaldehyde emissions. The industry has learned to adapt the well-known aminoplastic adhesives and the relevant processes of their production and usage to meet the standards that make it difficult to discern product emissions from background formaldehyde levels under standard indoor conditions.

The lignin-based adhesive sector has also changed significantly. Although in 2017 most researchers and companies showed their effort in implementing lignin-based adhesives for wood industry, today a range of real products are available that mostly replace part of the phenol in PF resins. However, the long-lasting dream of a pure lignin-based adhesive, without any use of other synthetic chemicals such as cross-linkers, and fulfilling the huge demand of the industry in terms of tons used, is not yet reality. However, work on such natural and sustainable wood adhesives will continue.

Strengths

Probably the greatest strength of the wood adhesives industry today is that it is essential for delivering society's interest in lowering carbon dioxide emissions and in using renewable materials by binding lignocellulosic raw materials into useful products. Between corporate commitments, government regulations (especially in Europe), and customer preference or demands, the interest in wood products is historically high. Long-lasting wood products often have a lower greenhouse gas emission footprint during production, i.e., low embodied emissions, than do competing materials such as concrete and steel, and are themselves a form of carbon sequestration (Bergman et al. 2014, Amiri et al. 2020, Churkina et al. 2020). One ton of wood consumes approximately 1.8 tons of atmospheric CO_2. Adhesives make possible wood products that serve a multitude of markets, from multistory apartments to single-family houses, and including interior work and furnishing of homes and offices. Life cycle analyses (LCAs) are tools to quantify the environmental impact of products and provide a means to quantify the environmental cost vs. benefit of various material options. LCAs for wood products and the environmental product declarations (EPDs) that result are being rapidly developed and are collected at www.corrim.org.

The forest products industry should be able to capitalize on this opportunity because of the inherent carbon emission advantages for wood products. This is the industry with the infrastructure and knowledge of how to use these materials. The wood adhesives industry is crucial to the use of wood products; most wood products contain adhesives, and larger size products are not possible without adhesives.

Despite significant effort to develop bio-based adhesives many targets for bio-based adhesives have not been met (see below under weaknesses); nevertheless, wood products are a logical bio-based substrate to pair with bio-based adhesives (Dunky and Mittal 2023).

Weaknesses

Slow progress in bio-based adhesives

Despite the great interest in bio-based products and extensive research on bio-based adhesives for wood (Ferdosian et al. 2017; He 2017; Hemmilä et al. 2017; Pizzi 2018; Dunky 2020, 2021; Dunky and Mittal 2023), the current consumption of bio-based adhesives is extremely low, estimated by multiple industry experts at well below 1 percent of the total wood adhesive market. There are no global statistics available on the volumes of naturally based adhesives and detailed information is very hard to obtain, forcing the authors to rely on their experience. The wood industry is by far the biggest adhesive user (Tobisch et al. 2023); therefore, we assume most bio-based adhesives are used in wood. A summary of implemented applications of naturally based adhesives is given by Dunky (2023c), About 20,000 tons/yr of soy-based adhesive is used in the North American hardwood plywood market (Orr 2007).

Why have bio-based wood adhesives made so little progress? One reason is that the petrochemical, mostly natural gas-based, adhesive industry has had 80 years of industrial experience for steadily improving their products. Modern UF resin is a perfect example of this development. Formaldehyde content and formaldehyde emissions have declined significantly (Dunky 2018, 2023a; Goncalves et al. 2018; Solt et al. 2019), with emissions close to natural dried wood under normal room conditions. In the process we have discovered that the basic chemistry between just two raw materials, urea and formaldehyde, is much more diverse (and exciting) than we thought two decades ago, especially influenced by the significant change in the composition of the UF resin, i.e., reduction of content of formaldehyde. New, naturally based adhesives have a double handicap: first, they have not achieved the high overall performance as that of the established adhesives without dramatically increasing cost and carbon footprint; and secondly, the barriers to market entrance related to price and performance kept getting raised as a result of improvements in established adhesives. New adhesives must not only bond wood at a reasonable price, but also deliver a specified degree of moisture resistance, fast cure rates enabling high production rates, and many other factors needed for the diverse array of wood products and their production process. Despite the significant price increases for simple aminoplastic resins during the past 1 to 2 years, these adhesives are still among the least expensive chemicals to produce. This largely explains the huge market share of UF resins (partly fortified with small amounts of melamine), which we estimate at ~85 percent of all wood adhesives worldwide, or ~15M tons/yr.

There is one more important feature of the wood adhesive market and, hence, a weakness of the bio-based adhesives. The adhesive demand is in millions of tons per year. Potential raw materials need to be consistently available in huge quantities. The list of raw materials available in such volumes and at low price is relatively short: lignin from papermaking, carbohydrates from major crops, or protein from the highest volume oilseed crops: soy (353 M tons/yr), rapeseed, sunflower seed, peanut, and cottonseed (70 to 40 M tons/yr; Statista 2022, UN FAO 2022). In some circumstances, bio-based raw materials such as tannin are economically competitive, but available volumes remain limited. Indeed, there had been in the past decades production sites in South America (e.g., Chile) and in the United States for the tannins by extraction from various natural sources, but these facilities have closed. South Africa continues to use tannin extracts. Highly abundant and relatively inexpensive raw materials such as lignin or soybeans have so far required significant amounts of manipulation or additional, higher cost ingredients to deliver acceptable performance. While bio-based materials can be advertised as NAF (no added formaldehyde), fulfilling the wish of the market to refrain from using synthetic and fossil raw materials, direct one-to-one replacement of synthetic adhesives without additional performance or properties and with the guarantee that no loss of efficiency occurs, will be difficult.

Another significant challenge to bio-based adhesives is the lack of fundamental understanding of process–properties–performance relationships. It is remarkable that it is so difficult to define what properties are needed for the creation of successful wood bonds, much less the characteristics of a material that will succeed. It is easier to determine why bonds fail than to determine what elements make it successful. For most bio-based resin systems, it is not understood what adhesive properties are critical to performance, whether concerning the raw material, adhesive processing, or product assembly. The literature on bio-based adhesives contains far more articles about the success of a particular formulation than of papers devoted to rigorous testing of hypotheses on the mechanisms and robustness of the performance under realistic, commercially viable production conditions. In the field of protein-based adhesives, e.g., many mechanistic explanations have been reported, such as exposing reactive groups during denaturation to enhance strength development, for which the evidence is thin or contradictory. Another common limitation of the literature is incomplete description of the bio-based raw materials used. Until the fundamental process–properties relations of these systems are clarified, misconceptions will continue to hamper progress. In contrast, the long experience with petrochemical adhesives has given time to develop a deeper understanding, resulting in synthetic adhesives being tailor-made to their application. For example, UF for poplar (*Populus* spp.) PB typically has a higher degree of condensation than does UF for PB of other species, attributable to the low density and the open structure of poplar resulting in higher penetration of voids (Gavrilović-Grmuša et al. 2012). This shows that aminoplastic adhesive resins (as well as other synthetic adhesives) are well-understood and tailor-made in their molecular features to maximize bonding efficiency (Dunky 2023a). Similar basic characteristics should be also valid for naturally based adhesives but are not yet explored in full scientific depth.

Another challenge for bio-based adhesives is that their feedstocks are dramatically more complicated and variable than are chemical feedstocks, which are based on defined synthetic chemicals of consistent composition and quality. Lignin and protein feedstocks for adhesives, e.g., are much more heterogeneous in chemical structure, molecular weight, and especially in proteins, aggregation state than petrochemical feedstocks. Most also contain significant quantities of carbohydrates. It can take years of experience working with natural raw materials before it is understood how raw material variations affect process and product performance. Many research efforts (small companies, universities) are isolated from the practical experience of working with bio-based adhesives in a production environment and do not have a deep understanding of the raw material. Networks and deeper collaborations would likely accelerate progress.

Broad-based challenges

The wood adhesive industry faces ongoing challenges because regulations and practices are constantly changing. One area of special interest to adhesives is the changing wood supply. Faster rotation forests and changing species availability means that manufacturers are often forced to adapt their processes. The material properties of wood gradually change over time because of these factors. In the United States, there has not been enough interest in characterizing properties of modern wood sources (other than southern pine) to justify updating references such as the wood handbook (Senalik and Farber 2021). An even more prominent aspect is the increased proportion of recycling wood in the production of wood-based panels, which poses not only the question of cleaning and separating recycled wood from nonwood components (i.e., all the various materials obtained when recycling old furniture), but also the question of the proportion of individual wood species in the recycled wood as they are finally inserted into the panel production process. In the majority of cases, it is difficult or even impossible to monitor exactly the composition of such wood mixtures, and even less information is given concerning variations in composition with time. However, it is well-known that different wood species or wood mixtures can behave differently in the panel production process (Hunt et al. 2019).

Finding and retaining employees is a perennial problem for the forest products industry, and hence affects bonding of these products. The attendees felt that labor shortages are exacerbated by public perception that cutting trees is environmentally unfriendly, or that working in wood industry is equivalent to being a lumberjack without intellectual challenges. Compounding this is the fact that most forest products production facilities are far from urban centers, which are not attractive to many employees.

Opportunities

Opportunities generated by interest in renewable content

Market opportunities identified during the discussion at the Wood Adhesives Conference inevitably included demand for biobased adhesives due to regulation or fear of regulation, as well as consumer demand. Biobased adhesives will not only be demanded for interior panel products but also for packaging and products of shorter life. Customer demand for biobased adhesives is not based so much on health-related issues, but mainly on the wish to replace fossil raw materials and general ''green motivation.''

There was also a consensus among the attendees that the advantages garnered by bio-based products will continue to drive demand for renewable engineered wood products (EWPs), with lower embodied environmental footprint to replace steel and concrete in construction. This can lower the carbon footprint over the entire life cycle while sequestering carbon in buildings. Bio-based adhesives have the potential to lower greenhouse gas (GHG) emissions for wood panel products. UF is estimated to produce 1.5 kg of GHG per kg of adhesive (Athena 2022). As a result, IKEA management supports switching to bio-based adhesives because the adhesives used to produce panels used in IKEA products account for 5 percent of all of the company's GHG emissions (IKEA 2021).

Novel bio-based adhesives face a much larger hurdle in the EWP market than do interior products because of the stringent performance requirements for structural products. Providing bio-based versions of traditionally petrochemical products based on bio-gas as replacement for natural gas or green hydrogen should be possible from a chemical and/or technical point of view, but with uncertain economic feasibility (Dunky 2022). These could move quickly into structural applications. They currently lack affordability and volume, but they should be potential alternatives in the midterm.

There is a general need to improve the performance of bio-based adhesives. Currently, all the low-cost bio-based materials available as primary sources need significant modification to meet production and performance expectations of industry. UF remains low cost, even with the extra costs associated with reducing formaldehyde emissions and the recent increase in prices for fossil raw materials and energy. However, these price increases, especially of energy, also affect the bio-based adhesives.

It is safe to say that all the bio-based adhesives could capture more of the market with a better performance/cost balance. The bio-based adhesives that can successfully compete with UF are most likely to come from low-cost, high-volume raw materials, such as sucrose (Rosenfeld et al. 2022, Sailer-Kronlachner et al. 2022) or with use of low-cost additives such as minerals. The relevant chemistry, however, still needs significant improvement, in order to keep up with the UFs. Soy flour is produced in high volumes, but soybeans cost 300 to 600 USD/ton, comparable with urea and formaldehyde. To date, soy has needed organic cross-linking chemistries. Polyamidoamine epichlorohydrin [PAE] and isocyanate have been most common (Li 2007, Birkeland 2021), reducing the bio-based content and significantly increasing cost. MgO, an inexpensive mineral, is also used with soy flour (Jang and Li 2015, Li 2016) but its performance and production volumes are limited. It is common to put up to 30 percent fillers and extenders into many petrochemical resins, especially those used as adhesives for plywood and solid wood bonding; and so bio-based materials are often incorporated in this manner. On contrary, adhesives for particleboard, OSB, and MDF/HDF do not contain fillers or extenders. Unfortunately, it is extremely difficult to obtain the actual recipes and production volumes to know whether an advertised ''green adhesive'' contains significant bio-content or whether any significant volumes are actually being produced.

Comparing established and bio-based adhesives always needs a clear understanding on the relevant application and, especially, potential impact of moisture and water. For indoor use in dry conditions bio-based adhesives have to compete against UF (and partly mUF = UF with small amount of melamine); for moist conditions, they have to surpass MUF (with different content of melamine, depending on the moisture conditions), PF, or pMDI. Here the products have higher value, but also the adhesives are more expensive because of the higher performance standards. So far, cross-linkers are mostly still synthetic chemicals, but naturally based cross-linkers are being developed in earnest (Dunky 2023b).

Opportunities generated by new and/or improved functions or performance

Many new functions were identified that could provide value to wood adhesives. Incorporating sensing functions so that the finished products can provide information about the structure of component or reporting on the building condition could be valuable, especially in applications where structural elements are difficult to access. Self-healing adhesives are commonly cited as a desirable product (Wang et al. 2019, Gao et al. 2020, Liu et al. 2020, Tang et al. 2022). Such a self-healing adhesive could potentially heal before a defect reached critical size. It is notable that, e.g., a building may survive an earthquake but still be so damaged that it must be demolished. Replacing metal fasteners in mass timber construction with adhesives was mentioned multiple times.

Adhesives have a potential role in additive manufacturing because the applied material has adhesive characteristics—flowing during application, then adhering to the previous layer and become solid. These applications may need special formulation or development, but it is already common for adhesive suppliers to customize products for individual (large volume) customers. Improving performance, such as developing structural adhesives for European hardwoods, is highly desirable as Norway spruce (*Picea abies*) dies off in droves throughout Europe. The attendees also spoke about the opportunities in bonding wood to other materials and in using waste streams as raw materials.

Continued tailoring of adhesives for specific uses, if it comes with performance benefits, is an ongoing opportunity, especially in high value, sophisticated applications. A reversible adhesive would be a straightforward way to advance the circular economy (Jarach and Dodiuk 2023).

Opportunities from changing building code

Interest in mass timber and cross-laminated timber (CLT) is also a great opportunity for wood adhesives. While CLT has been in use for many decades, its use in mid- and high-rise construction is more recent and generating interest in wood products. Recent changes to the 2021 International Building Code (IBC) for Type IV construction will enable structures using mass timber to be built higher than the historical 6-story limit (International Code Council 2021). The current code allows mass timber buildings to be a maximum of 18 stories or 270 ft (82 m), where the structural wood members are fully encapsulated and have a 3-hour fire resistance rating (FRR). Mass timber building with exposed wood members, within specific IBC limitations, and have a 2-hour FRR can be constructed to a maximum of height of 12 stories or 180 ft (55 m). Mass timber buildings with wood members exposed beyond the IBC limitations are limited to a total building height of 85 ft (26 m) and a maximum of 6, 8, or 9 floors based on occupancy type.

European Commission Opportunities for the industry overall

The interest in bio-based materials is also an opportunity to reframe the image of the forest products industry from lumberjacks destroying nature to leaders in the new low-carbon economy of the future. If this change in public mindset occurs, it offers the industry much better access to the talent pool both in direct hires and through collaboration with academia and government.

The entire wood products industry can benefit from improved tools to generate value from the desire for a low-carbon economy. This includes encouraging incentives for green building, participation in setting standards for green building, collecting and organizing the relevant data through EPDs and LCAs, and updating building codes.

An impressive example of a new wood-promoting program is the New European Bauhaus (NEB) Initiative of the European Commission (EC 2022a). The NEB is a creative and interdisciplinary initiative that connects the European Green Deal to living spaces and experiences. It calls on all of us to imagine and build together a sustainable and inclusive future that is beautiful for our eyes, minds, and souls. This initiative calls for wood and wood-based products to be the preferred construction material, from esthetic point of view and concerning mitigation of climate change.

The second big initiative of the European Commission is the ''Renovation wave'' (A Renovation Wave for Europe—Greening our Buildings, Creating Jobs, Improving Lives; European Union [EU] 2020a). Renovating both public and private buildings has been singled out in the European Green Deal as a key initiative to drive energy efficiency in the building sector and lower future carbon emissions. The NEB and the Renovation Wave both provide an opportunity for wood-based products and wood adhesives.

Quantifying and publicizing the environmental benefits of wood products would have many additional benefits, such as making industry more attractive to students and potential hires, assist in promoting wood use, encourage use of wood in other sectors, and encourage others to learn about and from wood. Many engineers, architects, and others currently dismiss wood and wood products as uninteresting, low tech, or not worth research. In addition, students often are not taught the tools needed to use wood in structures. Students in these programs often graduate without any exposure to wood and its properties, and so they are hesitant to work with wood. Getting wood included in the curriculum could have large, long lasting effect on wood use in the future.

The quality of academic and government research can in many cases be improved by a better understanding of the industrial state of the art and industry needs. Many in industry lament academic research efforts of limited utility because the academics lack critical knowledge. Solving this is at the heart of the Wood Based Composites Center, where industrial sponsors propose projects that are then taken up by students, with continued input of the sponsors throughout the research process. Another way that this is being addressed is through revival of the FPS (Forest Products Society) Technical Interest Groups (TIGs), where industrial and academic members can discuss common interests and issues. FPS and other technical conferences also provide a venue for academic and industrial researchers to discuss priorities and potential research directions. To realize these gains, members of industry must be willing to share useful information. It was pointed out that understanding the value chain up to end costumers also offers an opportunity to provide value. For example, building in qualities that add value to your customer's customer is a well-known way to use market pull to sell product.

Opportunities in recycling of wood and circular economy

The wood-based panel industry is in the best position for recycling wood and wood-based panels as part of the circular economy. ''The circular economy'' means that CO_2 shall be kept within products as long as possible before emission due to burning. This goes hand in hand with the European Commission's very demanding plans for the reduction of CO_2 emission of 55 percent by 2030 — ''Fit for 55'' (EC 2019, 2022b) and ''net zero'' by 2050 (UNFCCC 2020, EC 2022c).

Reusing and recycling wood products after their first life provides opportunity to stretch wood supply using adhesives (Nguyen et al. 2023), especially for products like particleboards (PB), which can more easily use ''waste'' wood, bamboo, bagasse, or other retired lignocellulosic products. Waste furniture and other wood products have been successfully transformed into particleboard for many decades in Europe and Asia. In several countries, all wood waste is reclaimed and used for either fuel or furnish. The proportion of waste or recycled wood related to the total wood demand in the various particleboard plants in Europe ranges from near 0 percent to nearly 100 percent; however, this variation means we have been unable to establish a general average for Europe. Recycled wood can come from construction residues, demolished buildings, pallets, cable drums or packaging. Old furniture is also a substantial source of recycled wood. Sophisticated and laborious procedures are necessary to clean the material, removing all nonwood portions such as metals, paper, plastics, foils, or foam. A special need of the particleboard industry is the removal of fibers, e.g., from old MDF or HDF boards.

For the MDF/HDF production, the use of recycling wood is still a challenge, with several attempts ongoing, such as the EU-sponsored Horizon Europe project ''EcoReFibre'' (EcoReFibre 2022). Whereas plywood cannot use recycling wooden materials, in OSB particleboard-like core layers are possible (Mirski and Dziurka 2011a,b; Schild et al. 2021).

Threats

Especially when pursuing novel high-profile, high-cost, projects such as very tall mass timber buildings, a few high-profile failures in new products can give the entire field a bad reputation. For example, CLT not properly protected from moisture could subsequently delaminate, decay, or become infested with insects. Another potential liability is exposing wood on the exterior surface without proper rain and ultraviolet protection, with subsequent peeling of coatings, mold, decay, etc. Standards will need updates, supported by sound scientific studies, to minimize these risks. The need for skilled labor in the industry, and the changing wood supply, can be seen as threats but have already been discussed.

Chemical regulation

Volatile organic compound (VOC) emissions from wood products are a potential industry-wide threat. While most of us enjoy the smell of fresh wood, the compounds that generate this odor are technically VOCs. We already face stringent demands on formaldehyde emissions and regulation of VOC emissions from the pressing process. Lingering concerns about air emissions have the potential to spark concern about naturally occurring volatiles in wood.

In Germany a very strict regulation was enacted concerning VOC emission from construction materials. No difference is made between ''synthetic'' VOCs (e.g., via adhesives) and ''natural'' VOC from the wood. The two main criteria—interalia—for the toxicological effects (harmful vs. not harmful) of the various VOC are, according to the Ausschuss zur gesundheitlichen Bewertung von Bauprodukten-Scheme (AgBB 2021), the sum of all VOC (''TVOC'') and the R value, describing the sum of the concentrations of the various VOC divided by their relevant lowest concentrations of interest (''niedrigste interessierende Konzentrationen'' [NIK]). The NIK values are a measure for the toxicological effect of VOCs. However, the court ruled these regulations of the Muster-Verwaltungsvorschrift – Technische Baubestimmungen (MVV-TB 2017) in the versions of federal regulations as adopted in Baden-Württemberg and in Bavaria did not account properly for toxicity by not considering different toxicological endpoints of the various VOC (Baden-Württemberg 2020, Bavaria 2021). The newest version of the MVV-TB (2023) was published, transferring these court decisions into law. Although this approach was dismissed for particleboards and OSB in Germany, there is concern that similarly stringent VOC emission standards, affecting many bonded wood products, could be enacted.

Regulation of several chemicals associated with wood panels have the potential to disrupt the industry. Melamine was classified as SVHC (substance of very high concern) in the European Union (European Chemicals Agency [ECHA] 2022) in December 2022. How to regulate melamine is in discussion and the topic of court cases in Europe, and may range from extra paperwork and little process change to banning melamine in UF, MUF, and MF adhesives. It is the authors' opinion that it will be extremely difficult for UF adhesives to pass formaldehyde emission standards without melamine, resulting in an enormous disruption to the industry. If melamine is severely restricted, the widespread use of MF and MUF for the production of hard, clear surface layers such as Formica would also be under pressure.

Formaldehyde emissions from up-to-date wood-based panels are extremely low, and as a result the UF adhesive and PB process of today is dramatically different from 20 years ago. The European Commission has just issued a regulation to lower the formaldehyde emission limit in a climate chamber from 0.1 ppm according to EN 717-1 (British Standards Institution 2013) to 0.05 ppm using the almost identical method described in ''Appendix 14'' in Annex XVII to Regulation (EC) No 1907/2006 REACH (European Union 2023). This new limit (European Union 2023) has now come into force with a transition period of 3 years. There had been other proposals on the table, which would have had the consequence of eliminating aminoplastic resins (UF, MUF), leaving only pMDI as adhesive. However, the volume of pMDI available would have been far insufficient to serve the whole wood-based panels market.

There are other examples where new and more stringent regulations on chemical exposure had been proposed. In some cases, wood-based panels could show that these limits are already met before the regulation was finalized. Other restrictions, such as for TiO_2, have been repealed by court decision in a first step (Court of Justice of the European Union 2022), but still not finally decided. For other cases, such as limiting the concentration of isocyanates at working places, new limits and need for training of all workers handling isocyanates have been defined (EU 2020b).

Raw material availability and costs

Climate change and global warming have already caused severe impact on forestry and the available wood species. Softwood generally is susceptible to the changing growing conditions, including higher temperatures and less rain and, hence, moisture available for the forests. One of the consequences will be that forestry will change in the upcoming decades, and changing weather patterns will change the future timber supply, potentially limiting the supply of softwood, which has traditionally been the majority of wooden products and wood-based panels. Among others, adhesive bonding of hardwood can be quite different from that of softwood (Berthold et al. 2017).

The past 2 years have caused tremendous increase in raw material costs, with the most prominent being natural gas (and subsequently adhesives). Recently prices have fallen back somewhat, but clear predictions are simply not possible. Return to price and cost levels equivalent to the end of the 2010s looks unrealistic, however.

One big threat for the wood-based panels industry is the strong competition for fresh (virgin) wood as raw material. This is especially acute in Europe where the dominant softwood, Norway spruce, is dying off. Beside solid wood and structural products (furniture, construction wood, laminated beams, glulam, construction wood, etc.) as well as panels, wood is also used for

- pulp and paper,
- bio-refineries,
- and direct energy generation by burning of biomass to replace fossil fuel.

As an example of allocation of wood industries' byproducts, a study in Finland (Kunttu et al. 2020) adopted a scenario analysis approach using qualitative and quantitative data, where the industry, research, interest groups, and policy experts formed and reviewed three scenarios, i.e., (i) pulp and bioenergy, (ii) versatile uses, and (iii) long-lifetime products. The study suggests that most wood byproducts in Finland at the time were going to fuel, but this should be changing with new EU directives, such as the Renewable Energy Directive (RED III). The aim of this study is to explore which options are considered preferable according to byproduct uses and why, and which actions are needed to reach those preferable byproduct utilization scenarios in the future. Scenario (i) was closest to the current industry structure in Finland and responding to existing needs;

scenario (ii) suggested material circulation and economic risk diversification, as well as fossil-to-bio substitution potential, but seen on a time frame of more than one decade; scenario (iii) highlighted the long-term carbon storage in wood products.

One danger is that public policy, including subsidies, will displace the cascade principle in determining wood flows. The logical cascade is to use virgin wood in high-value applications that take advantage of virgin wood's natural properties, and recycled wood in applications where virgin wood is not needed, e.g., for energy. When the fiber quality is low and/or contamination levels are high, wood can be incinerated as fuel. The European Parliament made the RED III decision on 14th September 2022 (EP 2022) to strengthen the cascade principle, because currently many energy plants are burning virgin wood while the wood-based panels industry fights with tedious material cleaning to recycle wood into panel products, particularly particleboard. The decision means that the share of virgin wood (high-quality wood contrary to wood byproducts from sawmills or damaged wood) as renewable energy in the EU will gradually decrease through 2030. This restricts the expansion of wood and biomass energy plants and helps to keep wood preferred in the materials circular economy. The EU Parliament did not vote to change the basic framework of maintaining the definition of forest biomass as renewable energy that can be used for RED target accounting. However, considering the risk that more use of forest biomass might increase forest harvesting, the share of forest biomass from total energy consumption is required to remain at 2017 to 2022 levels. Biomass will remain an energy source, but the cascade principle must be followed more closely: first reuse and recycling as often as possible, then finally, when material recycling is no longer possible, combustion for energy.

Burning wood might be ''CO_2-neutral'' in the long term, but time is essential. Using biomass for products where possible (cascade principle) sequesters the CO_2 immediately, without the delay of decades needed to regenerate the biomass to capture the CO_2 released in burning.

Consumer demands

Misinformed or conflicting consumer demands are always a risk, with the potential to derail good products or efforts, based on bad information or assumptions. The authors have multiple times seen statements that biobased materials are automatically biodegradable, that biobased materials inherently have lower environmental footprint, and similar categorically unsupportable claims.

Demands for no chemicals (adhesive or decay resistance measures) in wood products leave little room for innovation. Desire for extreme durability and easy debondability at end of life are inherently in conflict, as are expectations of durability and compostability, or the demand for carbon sequestration in products without harvesting forests.

Final Comments

The biggest contribution the wood adhesive industry can make to the well-being of future generations is to replace high-GHG products with low-GHG alternatives that offer energy efficiency, comfort, function, and long-lasting CO_2 sequestration. Adhesives have a significant role in this effort because they are essential components of most wood products. In addition, lowering the GHG intensity of wood adhesives is important because adhesives often represent a significant fraction of the total GHG load of the finished product.

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