Coatings and adhesives – a sustainable transition

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Summary

Modern coatings and adhesives are mostly made from fossil raw materials and are mainly a product of the chemical industry. Historically, coatings and adhesives were made from bio-based materials such as waxes, greases, resins or birch tar. Although with the emerging chemical industry more and more specialised products and materials based on fossil resources have been developed, the use of bio-based solutions holds great potential for this industrial sector and the bioeconomy. North Rhine-Westphalia-based chemical industry offers a powerful and established environment for a transition, which on the one hand can use increasing restrictions, but also customer requirements and the ambition to reduce the environmental impact of the coatings and adhesives sector as a motivator to realise the transition to bio-based products and value chains. Participation in research projects and increasing experience with alternative raw materials help to generate a constantly growing knowledge base and to establish bio-based products on the market. In the long term, this can support the defossilisation of the coatings and adhesives industry. Biotechnological applications have the potential to provide new speciality products for these markets and to support circularity and sustainability in the coatings and adhesives industry.

Zusammenfassung

Moderne Beschichtungen und Klebstoffe werden meist aus fossilen Rohstoffen hergestellt und sind hauptsächlich ein Produkt der chemischen Industrie. Historisch gesehen wurden Beschichtungen und Klebstoffe aus biobasierten Materialien wie Wachsen, Fetten, Harzen oder Birkenteer hergestellt. Obwohl mit der aufstrebenden chemischen Industrie immer mehr spezialisierte Produkte und Materialien auf der Grundlage fossiler Ressourcen entwickelt wurden, birgt die Verwendung biobasierter Lösungen ein großes Potenzial für diesen Industriesektor und die Bioökonomie. Nord Rhein-Westphalen ansässige Chemieindustrie bietet für eine Transition ein leistungsstarkes und etabliertes Umfeld, welches zum einen durch zunehmende Restriktionen, aber auch Kundenanforderungen und das Bestreben, die Umweltauswirkungen des Beschichtungs- und Klebstoffsektors zu verringern als Motivator nutzen kann, die Umstellung auf biobasierte Produkte und Wertschöpfungsketten zu realisieren. Die Teilnahme an Forschungsvorhaben und zunehmende Erfahrungen mit alternativen Rohstoffen helfen eine ständig wachsende Wissensbasis zu generieren und biobasierte Produkte am Markt zu etablieren. Langfristig kann so die Defossilisierung der Lack und Klebstoffindustrie unterstützt werden. Biotechnologische Anwendungen haben das Potenzial neue Spezialprodukte für diese Märkte zur Verfügung zu stellen und Zirkularität und Nachhaltigkeit in der Lack- und Klebstoffindustrie zu unterstützen.

Introduction

Coatings and adhesives are product classes that have become indispensable in various modern products. While historically biogenic materials were often used to create adhesive bonds or to provide materials with a functional coating, today fossil-based materials are more commonly used.

Coatings and adhesives are generally polymers with properties that differ depending on the chemical formulation of the product. Because of the complexity of the formulations, the technical nomenclature differentiates products by the process the polymers cure. This can be performed by physical triggers like a cooling process in hot melt adhesives, or a drying procedure that is used in many dispersion adhesives. The other mechanism, described as chemical polymerization reactions make use of addition, condensation, cross-linking and radical induced polymerisation reactions, which are also used in polymer-based coatings of synthetic resins. Chemical compounds commonly used in formulations are polyamides, polyurethanes, polyesters, and acrylates (1). [1]

Criteria for how well an adhesive or coating connects with the treated materials depends on cohesion, i.e., the interactions within the adhesive, and adhesion, i.e., the interaction of your coating or adhesive with the treated material. [1] In addition, there are various properties that depend on the chemical nature of the compounds used. Therefore, an adhesive does not simply keep different surfaces together, but may also act as a sealant against moisture, air, or chemicals. Following the same principle, coatings are not only products restricted to paints or resins but can be found in the form of metallic powders and even biogenic substances like proteins.

Coatings and adhesives are mostly invisible to consumers when they are used in industrial applications. However, the importance these products have on nearly all areas of the everyday life is high and reaches from the use in aircraft, automobile, and rail vehicle manufacturing, over medical and precision technologies like optics, to consumer markets like household chemicals and textiles [2]. Especially modern technologies like the lightweight construction through composite materials or special surface finishes in the medical or technical field need high performance ingredients from these product classes. This way, more sustainable materials and products can be manufactured, as materials are more durable due to higher chemical resistance or reduced deterioration. An excellent example can be seen in the construction of wind turbines, as a vital technology for the transition to renewable energies. The light composite materials used in the

[1] Industrieverband Klebstoffe e.V. - Leitfaden / Kleben
[2] Feica / Fraunhofer-IFAM - Adhesive-Bonding-Technology-21st-Century

turbine's blades can withstand the strong centrifugal forces and the steel build steles can be coated to be protected against atmospheric conditions [3].

Recently, the coatings and adhesives industry looks into more sustainable product formulations and welcomes green chemistry solutions. However, the transition to alternative feedstocks is not easily performed since formulations of products are complex and often rely on chemical precursors and the interaction of several ingredients. Nevertheless, the industry is on a path to increase the share of renewable feedstocks in their products to implement the United Nations sustainable development goals and tap alternative feedstock markets. This white paper will present some examples of renewable feedstocks for the coatings and adhesives industry and how biotechnology could be a source for new platform chemicals and high-performance ingredients.

Local markets of Germany and NRW

Products containing coatings and adhesives are plenty in everyday life and therefore the industries connected to these product classes feed into local and international markets alike. About 50 % of all produced products and construction services in Germany are connected to adhesives technologies, while the product variety on the market is estimated to 33,000 products in Germany. Worldwide there might be 250,000 different formulations available[4]. With production volumes in Germany of 1,137,000 tons of adhesives and sealants in 2018 this market holds great value for the local industry[5]. The same holds true for the sector of coating chemistry and suppliers, as the production of only the paints industry reached 2.6 million tons in 2016 of which 1.2 million tons were exported. The total sales volume is estimated to 8 billion € by the "Verband der deutschen Lack- und Druckfarbenindustrie e.V. (VdL) [6]. As two sectors traditionally connected to the chemical industry, several companies are located in the area of NRW with a strong network of suppliers of raw materials and buyers in the respective processing industries. The coatings and adhesives industry in Germany is positioned high in context of the international competition, with several of them within the top positions worldwide. [6]

[3] Fraunhofer IFAM - Klebstofftechnik und Kreislaufwirtschaft, p.42
[4] FNR - Biowerkstoffe: Nachhaltig verbunden
[5] Feica / Fraunhofer-IFAM - Adhesive-Bonding-Technology-21st-Century
[6] Beschichtungsunternehmen Deutschlands

Inviting a greener production process

The production of coatings and adhesives relies on long established chemical processes to deliver compounds of high quality and specific properties. The purity of precursors and products must be high to ensure that processes like polymerization and hardening of components function according to established guidelines to guarantee safe products. The main properties like the structural integrity of a bond or a sealant being able to withstand certain liquids are equally important as the fact that utilised compounds do not leach harmful substances, as products might be used for a variety of applications, including indoor use or food applications. Although established production lines deliver high performance solutions and probably would do so in the future, there are an increasing number of motivators that question the established production processes and invite the producing industry to rethink and reinvent compounds and value chains.

One major motivator is the creation of political guidelines and the overall commitment to the United Nations sustainability goals with the resulting EU- and worldwide agreements (e.g. European Green Deal, Circular Economy Action Plan, and Plastics Strategy). Accordingly, local strategies and policies are also influencing the industry and the development of markets. With Germany planning to quit lignite mining till the end of 2038 and the higher prices for natural gas and crude oil, the industry faces higher costs and resource insecurities. Recent shortages have shown that the availability of resource streams, that were considered to be secure, may vary. The development of alternative products and the consideration of biobased ingredients may give some extra flexibility to the producing industries, creating greater resilience. [7] The exit from fossil resources is only one aspect and goes along with a worldwide strive for the reduction of CO_2 emissions, a greener production in general, and the aim to circularise value chains, rather to build them linearly.

The growing accumulation of plastic waste in the environment is another issue, that has not only led to the ban of certain convenient one-use articles, like plastic straws and grocery bags, but underlined the necessity of effective recycling guidelines and an early eco-design. Products should not only show a good performance and user friendliness, but also an optimized and environmentally friendly production, value chain, recycling option and potential for a circular use of primary and secondary resources. [8] Especially for coated and glued products, this can be

[7] Fraunhofer IFAM - Klebstofftechnik und Kreislaufwirtschaft, p. 248
[8] Fraunhofer IFAM - Kreislaufwirtschaft und Klebetechnik, p. 82

problematic since the single compounds are difficult to take apart. Disassembling products for recycling works best in product specific disassembly lines, however the amount of energy and work might be comparable to the initial production. For complex products and heterogenic materials, shredding and sorting steps are therefore more common, even if this does reduce the recycling rate or e.g., in the case of plastic parts, the quality of the recycled product. [9] Since it is common practice to utilize non-recyclable materials only for their heating value, it is especially important that remaining adhesives and coatings burn without releasing harmful gases to the environment. For a design for recycling as a key factor, the formulation of the used products becomes more important. The planned guidelines for the right to repair, in connection with the goals of the European Green Deal, might additionally change production processes, especially when it comes to composite materials and glued parts in electronic devices. So detachable adhesive solutions should be considered as well. [10]

With REACH regulations taking effect in 2007 to improve the protection of the environment and human health posed by hazardous chemicals, the chemical industry increasingly faced more restrictions regarding product formulations. Of special interest are carcinogenic, mutagenic or reprotoxic substances (CMRD), but also chemicals falling under the persistent organic pollutants (POP) class. The list of substances included in the restriction dossier is growing and includes, among others, Bisphenol A, Formaldehydes, and Acrylates to be included in future amendments. [11] Since it is applied to all chemical products and impacts manufacturers, importers, and downstream users alike, many industries see themselves facing wide-ranging restrictions of compounds within the industrial production and the final products. [12]

With that being said, some established products might be harder to exchange than others. One major example are the restrictions and guidelines concerning the production and marketing of products containing perfluorinated organic compounds (PFC). The latest tightening on these regulations came into action starting 2023 for all EU states and prohibits the production, use, and marketing of perfluorinated carboxylic acids with a chain length of 9-14 carbon atoms. [13] [14] Especially in the coating sector many products, like textile treatments, non-stick coatings but also

[9] Fraunhofer IFAM - Kreislaufwirtschaft und Klebetechnik, p. 229
[10] Europäisches Parlament - Recht auf Reparatur
[11] Restrictions Roadmap under the Chemicals Strategy for Sustainability (europa.eu)
[12] ECHA - Understanding REACH
[13] Umweltbundesamt - EU beschränkt Verwendung weiterer PFAS
[14] Amtsblatt der Europäischen Union L282/29 (europa.eu)

everyday products like pharmaceuticals, cosmetics, shampoos, or household cleaning products make use of this substance class (2). Their unique properties as water, oil, and soil repellents and the general thermo- and chemical-stability contributes to the overall versatility and popularity since the start of their production in the 1940s. [15] The fact however, that PFCs related chemicals and precursors are, due to their stability, accumulating in the environment has led to a step by step restriction process that started in the early 2000s with the compounds perfluoroctansulfonic acid (PFOS) and has since then spread to a list of perfluorinated carbonic acids. Since POFs are rather hard to substitute, periods of transition and limit values have been established. [17] In most cases, the all-round performance of alternative compounds is lower, creating the necessity of more alternatives, that are tailored to single applications, or have to be combined to meet specifications. In the past, this led to companies often switch to other perfluorinated molecules for their formulations, that were not yet listed in restrictions and thus only shifting the problem. The latest EU-wide restriction regarding perfluorinated carbonic acids (PFCA) from 2021 shows, that this list is most likely to get longer. So, the change to alternatives that are ideally sharing the properties, but are easier to dispose of is inevitable. [18]

Lastly, it is the consumers who show a higher awareness for environmentally friendly products, so it comes as no surprise that the perception of the consumer is a driver for a more biobased production as well. While the adhesive sector is often overlooked apart from applications where adhesives are in direct contact with consumed goods, the use of coatings in everyday applications like to-go cutlery has been moved into focus by recent EU-wide restrictions and plastic banns. Indicators of the consumers tendency to request environmentally friendly goods show an increase in general consumer awareness for environmentally friendly goods, value chains and concerns for product safety. The last point being especially important for everyday products that come in direct contact with food. [16] [17] The increased awareness of consumers also includes recyclability of products and a design that allows for an environmentally friendly end of life management. Prices are still a main driver for consumers, however these motivators can be understood as chances to work on greener options and being perceived positively as a sustainably producing industry. First products show that the industry reacts to these demands and with that is driving the

[15] BMUV - Per- und polyfluorierte Chemikalien (PFAS)
[16] Umweltbundesamt - Konsum und Produkte
[17] Umweltbundesamt - Indikator: Umweltfreundlicher Konsum

transformation of the whole chemical industry and the establishment of new feedstocks and value chains.

Alternative routes through Green Chemistry

As mentioned above, biobased raw materials might add resilience to the production processes of coatings and adhesives. Classical material coatings and early adhesive solutions were based on biogenic resources, like beech tar in in the neanderthalian aera, and remained biobased until way into the industrial age. For example, wood glue based on glutin was used in carpentry and still is for its desired properties for the manufacturing of instruments. With the rise of synthetic polymers many biobased products were exchanged because of better properties of the synthetic counterparts, however some productions still rely on biobased raw materials (see below) and there are ingredients that might be reconsidered or optimized. The most promising renewable materials are biopolymers like proteins, or building blocks and monomers that can be given new functionalities by modification and polymerisation. The latter often even resemble existing synthetic solutions and therefore use similar processes. Lastly, biobased additives can be considered to alter or optimize the formulation of synthetic products (3).

Prominent renewable feedstocks

Apart from the above-mentioned historic materials there are renewable feedstocks that are performing well even in modern products and have great potential seeing a comeback, sometimes in a more refined form shaped by green chemistry or modern biotechnology.

As an example of an easily accessible renewable feedstock, starch and cellulose based adhesives are being used extensively on adhesive labels and the production of cartonnage. The fact that these adhesives are water soluble creates a benefit for easy peel of and recycling, especially in high throughput applications. As a fairly simple biopolymer, starch allows many chemical and enzymatic modifications to yield products with improved shear strength, water resistance, or thermostability (4). Chemically modified forms of cellulose like methyl cellulose and other cellulose ethers are classically used for the attachment of tapestry, but also have been adopted as thickeners and rheological agents. In a recent project, funded by the BMEL, cellulose fibres proved to be an excellent additive to coats and paints, where it could completely replace synthetic rheological agents and reduce the amount of solvents in the formulation. Modified cellulose nano particles had a positive effect on coverage and abrasion qualities of the products tested. [18] As a resource that is a main component of plant-based side streams, cellulose does not compete with the food production and is therefore an attractive starting material.

As another plant-based feedstock, woody biomass is rich in lignin, which can also be accessed as a side stream from the paper industry. Lignin is especially interesting for the chemical industry, since its structure can deliver aromatic building blocks for the chemical synthesis and replacing phenols in adhesive formulations. As an additive in resins, it could already be demonstrated that a replacement of 50 - 100 % of the phenol is possible (5). Recently, studies involving several Fraunhofer Institutes and German SME partners aimed for marketable solutions to use lignin in different formulations and products. As a result, lignin showed good performance in PUR-foams, PU-resins and coatings for fertilizers [19]. Depending on the source and the isolation method, lignin slowly becomes an important alternative building block for a magnitude of industrial applications and increasingly interesting on national and international markets (6).

Both (hemi) cellulose and lignin are of special interest, since they do not compete with the food production and are (generally) available as side streams from agriculture, forestry, or waste streams of the food industry. Interestingly, the xylan-fraction of hemicellulose is a well-known source of furfural, which is a base chemical from which many C4 and C5 compounds can be derived (7).

Another class of preferable feedstocks are plant based unsaturated oils, which are often highlighted in literature as a very versatile raw material for the synthesis of adhesives and coatings (8). In contrast to saturated oils, the double bond can easily be modified, and different functional groups allow a variety of different properties to be used in polymers. Due to these functionalities, vegetable oils can be used when it comes to the production of polyesters, polyurethanes, and epoxide-based polymers and are able to bring interesting properties to products like an enhanced hydrophobicity. The possibility of epoxidation makes plant-based oils compatible with other epoxy compounds and a modification of the alkyl groups to hydroxyl groups may provide the function to act as plasticisers (3). A prime example has been demonstrated by Evonik, where castor-bean oil was used as feedstock for the production of polyamids in their product Vestamid®Terra, which can be produced up to 100 % biobased and can already be found in different products from bulk plastic

[18] FNR - Cellulosebasierte Produkte für Farben und Lacke als Rheologieadditive und funktionale organische Füllstoffe
[19] FNR - Grüne Chemie: Polyurethane mit Synthesebausteinen aus Lignin

to the sports and fashion industry [20]. A second example was shown within the BioDur System developed by the Fraunhofer IFAM and industry partners. Here, epoxidized fatty acids were polymerised with polyols produces from lactic acid to create a 99 % bio-based adhesive. [21] These examples show that legal restrictions can act as an accelerator for the development of new, biobased products. [22] Polyamids can also be the base of above-mentioned hot melt adhesives, so vegetable oil might be an option for these products, too. An adaption of the above-mentioned feedstocks can already be seen in hot melt products. Jowat SE from Detmold advertises several formulations for the use in the wood, building, packaging and textile sector, showcasing the versatility of their GROW products, epoxide and polyurethane based hot melt blends, with a content of 20 – 50 % renewable ingredients. [23] [24]

In case of increasing restrictions of certain additives in coatings the search for alternatives for polyfluorinated compounds has revealed interesting biobased alternatives as well, although the solutions still lack the overall performance of oil, water, and dirt repellent properties given by PFAS. This made PFAS extremely convenient, especially for the food packaging industry, the textile sector, in household cleaning products, and as an additive for coatings in general (2). The more selective repellent properties of alternative sealants and coatings makes a broad application more difficult. For the resistance against oils and grease several polymers can be used. Possible alternative biobased products for the lamination of materials include polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), polybutylene succinate (PBS), and polyhydroxyalkanoates (PHA). Problems can however be found in the flexibility of laminations and the biodegradability and recyclability of finished products. However, lack of recyclability stands against the immense problem of PFAS accumulating in nature and the human body, because of their broad application and the stability of the C-F bonds (2).

PFAS alternatives in the field of textile treatment show that there are satisfactory products already on the market. Waxes, paraffins, stearic acid, silicones, dendrimer-based repellents, and nano structures can be used. The marketed products show excellent water/soil repellent properties at

[20] Evonik Industries - VESTAMID® Terra
[21] FNR - Grüne Chemie: Polyurethane mit Synthesebausteinen aus Lignin
[22] FNR - Klebstoffe auf Basis epoxidierter pflanzlicher Öle und hydroxyfunktioneller Polyester aus natürlichen Monomeren
[23] Jowat Klebstoffe - Grüne Klebstoffe in Möbeln und Gebäuden
[24] Jowat Klebstoffe - Biobasierte Klebstoffe

even lower prices, but higher concentrated formulations are needed. [25] As an additional hurdle, the alternative textile treatments should withstand washing procedures and abrasion, which can be problematic (9) An interesting feedstock for biobased coatings is chitosan, a polymer prepared from chitin via deacetylation. Currently, the chitosan used for industrial application is mainly derived from crustaceans, whose exoskeletons are available as waste stream derived from the food processing industry. The utilisation of this source however is problematic due to its regional and seasonal availability, as well as the economic aspects of redirecting the value chains for constant availability and the process of fractionating the chitinous waste (10). Alternatively, with the approval of insect-based protein in food products, chitinous carapaces might become increasingly available as a side-stream from the insect breeding industry, as a by-product of proteins extraction. Additionally fungal sources might become an interesting source, since chitin and chitosan are components of the fungal cell wall. Therefore, industries using yeasts and other fungi for fermentation might serve as a viable source (11) (12). Especially microorganisms or in general fermentative production of chitosan oligomeric substances are interesting in regions not connected to industries generating chitinous waste streams. Furthermore, the modifications that can be made by biosynthesis hold great potential for applications in biomedicine, drug delivery, coatings of medical equipment, but also agriculture, since degree of polymerisation, acetylation and other modifications can be regulated to yield the desired products (13).

The role of biotechnology

The above-mentioned examples show that it is possible to shift production into the direction of green chemistry principles and to integrate (novel) renewable feedstocks into formulations. In industrial scale, white biotechnology has proven to be an interesting tool to produce high-performance compounds. The open communicated use cases from the industrial production of the coatings and adhesives sector are still meagre, however the successful cases are growing. Many renewable building blocks can be produced by fermentation and the possibilities are manifold.

A product class with great potential for the polymer production are organic acids. The most prominent being lactic acid, which is already used in biobased PLA and produced in bulk for

[25] Danish Ministry of the Environment - Alternatives to perfluoroalkyl and polyfluoro-alkyl substances (PFAS) in textiles

industrial purposes. Although lactic acid can also be produced by fossil based chemical routes, the fermentative production in lactic acid bacteria (LAB) is advantageous because of the production of pure isomers and has been adapted as the main production route (14). Apart from PLA, lactid acic is versatile and can be used to produce polyesters and mixed with epoxidized fatty acids, as was featured in the above mentioned BioDur Project. [26]

Another commonly used compound is acetic acid. Acetic acid represents an important commodity chemical in the global chemical industry. Currently, the largest proportion goes into various polymeric materials and derivatives, including vinyl acetate monomer (VAM), acetic anhydride, acetate esters, as well as its use as solvent in the synthesis of terephthalic acid for polyethylene terephthalate (PET) production. While the main market share of acetic acid is produced by the petrochemical route via carbonylation of methanol, the share of bio acetate is only 10 % of the world-wide production. Here a two-step process is used which includes alcoholic fermentation using yeasts followed by the production of acetic acid by acetic acid bacteria. This bio based acetic acid however is exclusively used in vinegar for the food market. Still, with several companies world-wide picking up this biotechnological production of acetic acid, the market is expected to grow in the future (15). In the last years, acetate gained more attention not only as a feedstock for chemical synthesis but as a viable substrate for fermentation, itself. Although it often acts as an inhibiting factor in fermentations, the development of acetate tolerant or even utilizing strains creates new possibilities. In studies, acetate could be used as a co substrate to yield isobutyl-acetate, a solvent used in the production of colour and paints, and to boost the ethanol production in baker's yeast fermentation (16). As a matter of fact, most industrial relevant microorganisms are able to grow on acetate as a carbon source and the acetate metabolism yields acetyl-CoA and TCA-cycle intermediates, which are interesting precursors for value added products (15).

There are further organic acids that are relevant for the coatings and adhesives industry. Some of them are already produced biotechnologically on commercial scale, like succinic acid, or gluconic acid (17). A relatively new but promising platform chemical is itaconic acid, which can be used as a building block in several products, with unsaturated polyesters and methyl methacrylate as the most marketable ones. The main industrial production organism is *Aspergillus terreus*, however high yields with up to 220 g / L have been reported for *Ustilago maydis*. Efforts are also aiming at engineering yeasts and bacterial hosts for the production(18) (19). As the state of the art of

[26] FNR - Klebstoffe auf Basis epoxidierter pflanzlicher Öle und hydroxyfunktioneller Polyester aus natürlichen Monomeren

industrial production of itaconic acid is the biotechnologically route, the process suffers from fermentation related parameters. *A. terreus* is the predominant strain used for industrial production of itaconic acid, with yields of up to 160 g/L. But it still suffers from slow growth, shear intolerance of the mycelium, high fermentation viscosity, and a requirement for high oxygen supply. Furthermore feedstocks, downstream product separation, and purification processes are determinants of production costs (20) First attempts however have already been made to produce itaconic acid on 2nd generation feedstocks through co-cultivation principles (21). Although the yields are still lacking behind, these concepts may unlock hidden potentials in industrial biomass utilization.

Two recent developments for the fermentative production were shown for the chemical building blocks aniline, which is used in poly urethane manufacturing, and hexamethylene diamine (HDMA) that is used mainly to produce nylon 6-6, but also interesting for the coatings and adhesives market. In case of aniline the company Covestro from Leverkusen, Germany was able to optimize the fermentative production of aminobenzoic acid, which can then be decarboxylated to aniline [27] [28]. To produce HDMA, Covestro cooperated with Genomatica to launch the production of a completely plant based HDMA using a fermentation process. The automotive sector alone consumes 500,000 tons of HDMA per year in the form of PU coatings, making this a promising venture [29]. This shows that biotech solutions can present competitive solutions for chemical production. It´s application however is still underrepresented.

What is hindering the transformation process?

How can companies achieve the shift to a more environmentally friendly production and a more circular approach? Future products will have to meet the performance of existing products as a minimum to be considered as a viable alternative, since drastic changes of production processes are linked to major investments. Many of the transformational technologies are still at a low TRL and therefore often not tested above pilot plant scale. This scale-up process and the needed investments are not readily made by companies with many insecurities remaining in this relatively young market (8).

[27] Patent: WO2018002088A1 - Method for producing aniline or an aniline derivative
[28] Covestro - Auf dem Weg zum biobasierten Anilin
[29] Covestro and Genomatica produce important chemical raw mater

In the future, new solutions will be measured by their potential to work in line with strategies following the sustainable development goals. So, in the long term, not only the raw material shift to biobased resources has to be done, but also aspects like recycling and circularity will have to be considered. Especially recyclability requires chemical or enzymatic procedures and additional effort in the separation of the materials that as of today are not economical. The transformation is therefore not only the task of the chemical industry alone, but much more a whole industry effort with several stakeholders down the value chain including brand owners, retailers, advertisement and finally the disposal and recycling management.

The demand of a general biodegradability of coatings and adhesives also directly impacts their durability and performance (3). A shift to biobased solutions is often hindered by the extreme product specificity in the coatings and adhesives sector. Stationary adhesives like glue sticks are often based on modified starch and water, however, other applications demand much higher performances and more complex formulations, where biobased solutions, although showing good functionality, are lacking behind in adhesion strength or other properties (3).

Biobased concepts shown in research and small to medium scale demonstrations exhibit equally good or better environmental performance. First products on the market show that the transition is possible, and that the needed steps and investments are being made. For a comprehensive transformation however, it still lacks in research and a clearly and transparently communicated modelling of the environmental and economic benefits of biobased solutions (8). The above stated case of utilising lignin shows that years of research still leave behind several hindrances including the quality and origin of the feedstocks, isolation methods, the heterogeneity of the lignin product, low reactivity, and process residues that must be dealt with economically (3). [30] [31].

The above-mentioned advantages that biobased raw materials offer to former solely synthetic, fossil-based value chains come at a cost. Most renewable raw materials that are being industrially used rely on 1st generation feedstocks. This is especially true in cases where large scale fermentation is involved in the production process.

The costs for a biotechnological production is largely represented by the raw materials (22). The volatility of prices for sugar and other feedstocks for the industrial biotechnology is therefore an insecurity, also since they are used not only in the chemical sector, but also in other industries.

[30] Fraunhofer IFAM - Kreislaufwirtschaft und Klebetechnik, p. 247
[31] FNR - Grüne Chemie: Polyurethane mit Synthesebausteinen aus Lignin

Naturally the use in the food market is the most anticipated and political regulations will keep the scales tipping to the nutritional rather than the material use of primary sugars. Consequently, more flexible feedstocks would be most welcome, but will come at high costs and insecurities as well. So far, the utilisation of lignocellulosic biomass has barely entered the industrial scale and complex substrates like waste biomass are problematic because of their heterogeneity and inconstant availability. The requirements of processes to accept feedstocks of ever-changing availability and quality is demanding a robustness, that is hard to meet from a technical side. It is therefore important to understand the dynamics of renewable feedstocks and their supply and demand on the markets (22) and create new value chains around those feedstocks. Second generation feedstocks may in the long term be able to reduce the effects of volatile first-generation feedstock prices, however, the dependency on renewable first-generation feedstocks will continue in the near future.

Future perspectives

The product group of coatings and adhesives are well suited for the implementation of bio-based raw materials and alternative production pathways. On the one hand, when compared to bulk chemicals, the production volumes are smaller so that biogenic raw materials could be provided. On the other hand, the produced amounts are high enough to be able to run the production economically. This is especially true für speciality chemicals that fetch higher prices in low volumes. The complexity of tasks and functionalities the products must solve are high and thus the market constantly calls for new specialized products. This demand will not only focus on fossil-based products and compounds regulated by REACH but is already driving the development of biobased alternatives because of a stronger commitment to the SDGs by companies and consumers.

For the producing industry the diversity of formulations complicates the search for biobased chemical building blocks, but inn turn allows for creativity in new formulations, without disturbing existing value chains [32]. Research shows that biobased formulations can outperform fossil-based polymers, which can be seen for polyurethanes on the basis of vegetable oil polyoles (3). Additionally, the structure of biobased macromolecules can be an advantage, since it offers a complexity that is not easily achieved by chemical synthesis and functional groups that add unique reaction properties (3).

[32] Fraunhofer IFAM - Kreislaufwirtschaft und Klebetechnik, p248

In the future, several green key technologies of the energy and mobility sector will require high performance adhesives and coatings, like for example the manufacturing of products for the energy transition, or components for electric vehicles. [33]. Greener compounds and products designed for recycling will underline the positive environmental character of these technologies. This is especially true for sectors with high environmental impacts, like the construction sector. Recently discussed debonding on demand solutions could make a difference in how the end of life could be approached. Here, not only biobased formulations but different means of debonding technologies can bring new functionalities to products and contribute to the recycling strategies of multi layered materials in consumer products and packaging. [34] [35] Additionally, material-compatible debonding will have a huge impact on the reusability of electronic devices, which is a set goal within the "right to repair" debate connected to the European green deal and the strive for reduction of electronical waste. [36] Interestingly, switchable adhesion is also included within the framework of the flagship project Bio4MatPro under the industry partner Henkel AG & Co KGaA and university partners from Heinrich-Heine University Düsseldorf, RWTH Aachen, Bonn University, the Leibniz institute for interactive materials DWI, and the Forschungszentrum Jülich [37]. This NRW based project consortium is a good example for the transitional potential of the region.

The importance of the consumer in the transformation process is not to be underestimated. In contrast to the use in professional applications, coatings and adhesives are often invisible for the consumer and with this the knowledge, that these products allow for complex devices and products to be safe, light and durable. It is important that consumers are aware of these functionalities to appreciate the development of more environmentally solutions. The need for further awareness rising of consumers regarding biobased products was already shown within the HyperIn 2.0 report by Ahaus *et al.* (in publication). Therefore, companies can underline their social and economic responsibility by creating a transparent production process and highlighting benefits of green chemistry. Especially the partake of biotechnology is sometimes falsely tainted with irrational insecurities. The benefit that biotechnology can have as a boosting and enabling technology for the use of biobased raw materials and downstream processes is high and from the consumers side often overlooked. To show the innovative character of new products, the different

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[33] Fraunhofer IFAM - Kreislaufwirtschaft und Klebetechnik, p283
[34] Fraunhofer WKI - Bonding on Demand
[35] Henkel Adhesives - Für das Recycling gedacht
[36] Europäisches Parlament - Recht auf Reparatur: Warum sind EU-Rechtsvorschriften wichtig?
[37] RWTH AACHEN UNIVERSITY - Über Bio4MatPro

stages of research and development should be shared in an understandable way. This way an eco-friendly production and slightly higher priced products may be accepted more readily supporting further market growth.

NRW as a strong network for transition

The transformation of the coatings and adhesives industry rests on a strong base provided by NRWs chemical industry. The unique environment provided by this historically grown sector already led to first steps in the direction of green chemistry examples and will continue to do so with companies following the examples of early adopters. Here not only local players, but also globally successful companies are readily investing to include biobased ingredients into formulations. Good examples, among others, are the starch based PROLOC adhesive technology, or the biodegradable coating additive CERAFLOUR that was recently expanded by two additional wax like renewable biopolymers [38] [39]. Although biobased feedstocks are considered increasingly, biotechnology is still underrepresented in the chemical production. Research, however, shows great potential in proof of principle concepts apart from already established productions of bulk chemicals like acetate and others. Here biotechnology can serve not only for production of more specialized compounds but can be understood as a enabling technology, for example by treating raw materials enzymatically. (Guo et al., 2022). Interestingly the fossil based industry leads the way by applying new production concepts and taking part in larger research networks to directly bring research into line with marketability.

Political and environmental motivation hints to a higher share of green products needed and funding is being spent to further accelerate this process. The large number of research projects working on a higher share of biobased formulations shows a high interest in this transition. Here, NRW offers an excellent network of universities, research centres, and science networks. Established research partnerships to neighbouring countries further contribute to this knowledge base and might help to access interesting feedstocks in the future. The involvement of the producing industries in such projects adds additional know-how to access demands and requirements and therefore accelerate the development of market ready solutions. [40]

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[38] Henkel Adhesives - Polymere für die Arzneimitteldosierung
[39] ALTANA AG - CERAFLOUR 1001 und CERAFLOUR 1002: Nachhaltigkeit par excellence
[40] Biogener Klebstoff für die Industrie

For the future it is important to make further use of NRWs unique environment of interwoven industry, SME, research facilities as well as supplying and further processing industry.

New renewable feedstocks can be supplied by NRWs strong agricultural and forestry sector might be supplied by the neighbouring regions. CLIB will continue to strengthen these important cross-border relationships with projects like Realise-Bio to bring together collaborators with the mutual interest to establish sustainable value circles

As projects like HiPerIn and HiPerIn 2.0 shed light on the sustainability and performance of biotechnologically produced industrial ingredients, the future motivator has to be the scalability of promising concepts to create value chains that can compete with fossil-based pathways.

About CLIB - Cluster Industrial Biotechnology e.V.

CLIB (Cluster Industrial Biotechnology) is an international open innovation cluster of large companies, SME, investors, academic institutes, and universities, as well as other stakeholders active in bioeconomy. The cluster comprises over 100 members with a share of about 25 % international members. The overall goal of CLIB is to network stakeholders in Germany and beyond and to identify new opportunities for innovation, projects, and business. Through this, the cluster develops cross-sectoral biotechnological solutions for sustainable processes and products. CLIB is a non-profit association, with its members shaping the cluster's interests and activities. The cluster is involved in several associated programs which cover different aspects of bioeconomy and invites members to become involved. To this end, CLIB organises several events throughout the year: the annual CLIB International Conference (CIC), the CLIB Networking Day (CND), forum events, topic-specific workshops, and dedicated small partnering meetings.

About HiPerIn 2.0

HiPerIn 2.0 is a project funded by the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia (MWIKE). HiPerIn 2.0 reflects the rapid change in biotechnology and includes cross-cutting issues which had been identified and validated by CLIB and in an exploratory phase. The increasing digitalisation of biotechnology, the renewed concept of a circular economy, the end-of-life debate, the public perception of biotechnology, and increased regulatory requirements are cross-cutting topics which are of interest to many stakeholders. CLIB pursues the topics of biosurfactants, textiles, flavours and fragrances, and food/alternative proteins. Another focus in the HiPerIn 2.0 project is the support for project consortia and the identification of potential funding lines.

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