

BARRIERS AND INCENTIVES ON THE MARKET DIFFUSION OF LIGNIN COMPOSITES – A DELPHI-SWOT ANALYSIS

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Abstract:

In order to move towards a post-petroleum society, the use of by-products, such as lignin, offers unique opportunities. In terms of material use, lignin is an underutilized by-product of pulp and paper mills. It has interesting properties for composite applications, either as matrix component or as filler. Besides its contribution to the vision of bio-economy, the advanced use of lignin as composite could offer economic long-term benefits for stakeholders along the value chain.

The aim of this study was to identify barriers and incentives on the market diffusion of lignin-based composites. Additionally, supportive investigations on the potential bottlenecks along the value chain and the potential market development were conducted. Considering the value chain of lignin-based thermoplastic composites, 19 experts from the pulp and paper industry, research and composite production and application from across Europe and North America participated within the two-stage Delphi study. The 1st stage consisted of expert interviews, followed by summarizing and structuring of the derived key-factors into the categories strengths and weaknesses of lignin for composites, as well as potential opportunities and threats (SWOT). Thereafter, the SWOT analysis was reviewed and the three most important key-factors of each SWOT category were selected by the experts (2nd stage).

The conducted Delphi-SWOT analysis demonstrated various barriers and incentives, as well as the high interdependency between the potential stakeholder groups along the value chain. Besides potential barriers like odor and color issues, questions regarding the final field of application were derived. In general, the potential environmental benefits, as well as potential additional profits along the value chain are seen as incentives for the market diffusion. The establishment of industrial networks is considered as possibility to overcome existing bottlenecks. Besides the improvement of cost-performance relations, sustainability and environmental issues are seen as incentives for the future market development of lignin-based composites.

Key words: bioeconomy; Delphi method; lignin-based composites; stakeholder perception; SWOT analysis.

INTRODUCTION

Increasing environmental concerns and climate change call for a shift from the current fossil-based economy towards a sustainable bio-economy (Philippidis *et al.* 2017). While the benefits stemming from the transition to a bio-economy are quite diverse, the reduction of greenhouse gas (GHG) emissions and the decrease in dependence on fossil resources are seen as key-factors (Langeveld and Sanders 2010, European Commission 2012, McCormick and Kautto 2013).

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The forest-based sector (i.e. pulp and paper, solid wood products and downstream value-added wood-based manufacturer) can play a central role within this transformation (IEA Task 42). The future market development of the forest-based industries differs considering *traditional products* (e.g. saw wood, wood-based panels or pulp and paper) and *new or emerging bio-based products* (Jonsson *et al.* 2017). The European forest-based industries have undergone fundamental structural changes in the last years (Hansen *et al.* 2013), e.g. the decreased consumption of graphic papers (Jonsson *et al.* 2017). Therefore, it requires new thinking in line with the vision of bio-economy. The European markets are further influenced by the European Union's renewable energy target leading to a higher demand for energy wood (Solberg *et al.* 2014). For example, whereas the sawmill industry could profit by selling wood chips, bark or pellets, the particleboard and pulp and paper industries tend to suffer from the development of bioenergy because of higher prices for wood raw materials (Johnston and van Kooten 2016, Jonsson and Rinaldi 2017, Jonsson *et al.* 2017).

Since the 2000s, the concept of *new forest products* can be found on the policy and industry agenda. Besides the push from policymakers and others to reduce the fossil fuel dependency, the forest-based industries are also seeking to diversify their product portfolio and enter new markets (Jonsson *et al.* 2017, Philippidis *et al.* 2017). The use of by-products following a cascade principle in order to maximally valorize the available biomass fits into the concept of bio-economy (Van Lancker *et al.* 2016). Although studies (Cologne-Paper 2007, Bünger 2010) have shown that 90% of petrochemical-based products could be replaced by bio-based alternatives, up to date only a few alternatives are available on the markets (Golembiewski *et al.* 2015, Van Lancker *et al.* 2016). Due to the increasing interest in bio-based materials, lignin as a by-product of pulp and paper industries has gained in importance (Gosselink *et al.* 2004).

The pulp and paper industry, as the primary source of technical lignin, produces currently worldwide around 50 million tons of lignin per year. Despite the large annual production, only 2% are used for applications, the rest is used for energy purposes needed for the pulping process (Haghdan *et al.* 2016). Although research on lignin already started around the 1950s, a successful, large-scale market diffusion has not taken place to date. One reason is that the research on lignin extraction and utilization has been highly empirical and raw-material-based rather than practice- and application-oriented (Gosselink *et al.* 2004).

Whereas current scientific literature in terms of bio-economy mainly focuses on technical aspects (e.g. production and processing of bio-based products) or on related environmental and social consequences (Pfau *et al.* 2014), the issue of market diffusion of new or emerging bio-based products is still underrepresented.

In order to gain knowledge on the market diffusion of lignin and lignin-based products, it is necessary to integrate potentially involved stakeholders along the value chain. Whereas studies on lignin for adhesives, polyurethanes and phenol-formaldehyde resins have been carried out, only some studies have been published on lignin-based polymer and polymer blends (Sahoo *et al.* 2011). Lignin is considered to be a promising compound in polymers due to its phenolic structure, which can lead to higher mechanical properties when incorporated in plastic (Thielemans *et al.* 2002). Studies considering market diffusion of lignin as raw material (Lettner *et al.* 2017) or as a replacement of fossil-based phenol for phenol-formaldehyde resins (Stern *et al.* 2012, Gabriel *et al.* 2017) have already been carried out. This study focused on the application of kraft lignin and liginosulfonates as thermoplastic components in composites and blend in combination with polylactic acid (PLA), polypropylene (PP) and polyethylene (PE). The objective of this study was to identify potential barriers and incentives for a market diffusion of lignin-based composites.

The following research questions were developed for this objective:

- q1: Which barriers are currently limiting the market diffusion of lignin-based thermoplastic composites?
- q2: Which incentives could foster the market diffusion of lignin-based thermoplastic composites?
- q3: Where are the current bottlenecks of a market diffusion along the value chain?

METHOD

Within the framework of the current study, a two-stage Delphi study in combination with a SWOT-Analysis was conducted. In order to derive various barriers and incentives for the market diffusion of lignin-based composites, the study includes expert knowledge from relevant industries and research organizations from Europe and North America. The research design is illustrated in Fig.1.

The Delphi method is a popular forecasting method under the circumstances of uncertainty or lack of data (Häder and Häder 1998). Therefore, expert opinions are combined with a group response (Powell 2003). The Delphi method is often applied to support decision makers with information about future events and developments, especially when it concerns high-cost investments (Häder and Häder 1998, Powell 2003, Landeta 2006). One major advantage of the Delphi method is that it is suitable for interdisciplinary and complex problems which are influenced by a variety of heterogeneous individuals (Välimäki *et al.* 2004). As a multi-stage expert interview approach, the same group of experts are questioned multiple times with intercalated feedback loops. The aim is to gain a consistent opinion within a diverse group of experts. There

is no standard for the number of rounds, but in practice two or three rounds are usual (Häder and Häder 1998, Rowe and Wright 1999, Powell 2003). Controlled feedback provides generalized information on the different opinions and judgements within the expert panel. Although the aim is to reach agreement among the experts, it is important to also show how much the different opinions diverge (Rowe and Wright 1999).

In this study, a two-stage Delphi method was applied. With regard to the value chain of lignin-based thermoplastic composites, experts from the following stakeholder groups participated: *pulp and paper industry, research and composite production and application*. The first stage represents a qualitative approach and consists of expert interviews (telephone or face to face). The aim was to get an overview on the topic by applying general open-ended questions divided into introduction, barriers, incentives and outlook. Based on the transcript, potential key-factors influencing the potential of lignin as composites were derived and structured into a SWOT matrix. This was the basis for the second round of the study.

The Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis is a popular tool, which is often applied in the field of marketing, management and personality development (Pelz 2004). Based on the subjective assessments of strengths, weaknesses, opportunities and threats, the SWOT Analysis is often used to investigate the current position of a company (Iemsomboon and Tangtham 2014). The results of a SWOT analysis can serve as the basis for almost every attempt of strategy development process (Hill and Westbrook 1997) and thus provide a starting point for making decisions for future developments (Pelz 2004). The four categories of strengths, weaknesses, opportunities and threats can be considered as an extension of the basic distinction between pro and con (Iemsomboon and Tangtham 2014). The categories strengths and weaknesses describe the internal influences, whereas the categories opportunities and threats describe the external influences (Hill and Westbrook 1997). The results of a SWOT analysis support the strengths, reduce the weaknesses, take advantage of opportunities and prepare against threats (Párraga *et al.* 2014). In this study, the SWOT matrix, compiled from the interviews conducted in the 1st stage, was sent to the participating experts (2nd stage). In order to gain information on the importance of statements, the experts were asked to choose the three most important key-factors of each category. Additionally, the experts were able to comment on the given key-factors.

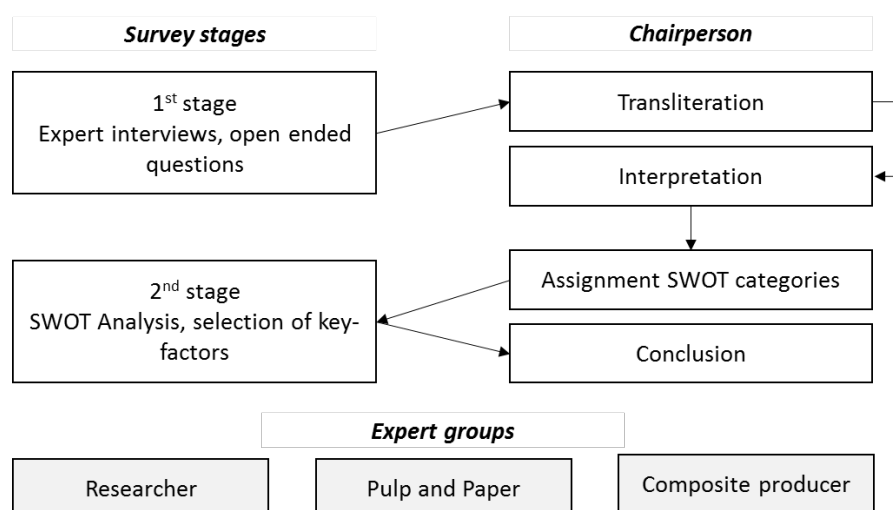


Fig.1.

Research design of the hybrid Delphi SWOT analysis and considered expert groups for this study (own representation based on Stern *et al.* 2012).

RESULTS & DISCUSSION

In total, 19 experts participated in this study: within the first stage, 7 experts from pulp and paper, 6 experts from the group of researchers and 3 experts from the group of composite producers. In the 2nd stage, 6 experts from pulp and paper, 7 from research and 4 from the group of composite producers participated. Apart from 1 expert from the group pulp and paper and 1 expert from the group of researchers, all experts from the 1st stage participated within the 2nd stage. Additionally, three experts who were unavailable for the 1st stage participated within the 2nd stage.

As has been previously mentioned, the key-factors were derived from the 1st stage and afterwards presented to the participating experts (2nd stage). For each SWOT category, a total number between 13 and 19 key-factors was given. The participating experts then chose the three most important statements for each category. Table 1 shows the three most frequently chosen factors for each category.

Table 1

Ranked results from the SWOT analysis (own representation)

Strengths	Weaknesses
1. Environmental benefits	1. Odor
2. Bio-based product	2. Color
3. Availability	3. Quality
Opportunities	Threats
1. Profits for pulp and paper	1. Cheap Crude oil
2. Sustainable product demand	2. Lower performance
3. Substitution of fossil oil // brand-owners	3. Missing applications

Whereas the strengths are mainly related to the fact that lignin is a bio-based polymer, the weaknesses and threats are mainly reflecting potential technological disadvantages. In both cases, economic aspects, e.g. additional *profits for the pulp and paper industries* as an opportunity or the availability of *cheap crude oil* as a threat, can play a key-role for the market diffusion of lignin and lignin-based products. It is noteworthy that the most important key-factors are often directly linked to lignin as raw material (e.g. key-factors like *costs, availability and quality*). This is also in line with the results provided by Stern *et al.* (2012), showing that for a market diffusion of lignin-based products the most frequently seen barrier is the lignin itself. In the following sections, the main barriers and incentives for a market diffusion of lignin-based composites, derived from the conducted expert interviews, are discussed in more detail.

1. Barriers for the market diffusion of lignin-based composites

According to the participating experts, the main barriers, ordered from high to low performance, for utilizing lignin as raw material for composites include:

The odor of lignin-based composites: Due to processing and separation processes, sulfur-containing lignins commonly have an unpleasant odor (Vishtal and Kraslawski 2011). The issue of potential odor nuisance (e.g. associated with rotten eggs, sauerkraut or burnt wood) concerning lignin-based composites is mentioned frequently by the experts. Although this barrier is seen as currently limiting the market diffusion, it is noteworthy that experts are aware of the possibility to reduce the odor through various pretreatment steps e.g. further purification or by addition of oxidizing chemicals like hydrogen peroxide, as shown by Vishtal and Kraslawski (2011). The experts also propose a more practical approach: finding applications where the odor is not seen as a barrier; for example, outdoor application like construction parts.

The color of lignin-based composites: Lignin is colorless or pale yellow in nature, but the color changes to brown or dark brown after acid or alkali treatment (Agrawal *et al.* 2014). The experts agree that the typically darkish brown color of lignin-based composites could be a barrier for the market diffusion. Nevertheless, it is noteworthy that some experts mention that the color is not an actual barrier but it might limit the field of application. Furthermore, the experts even state that the color could be an incentive, if the potential end-consumer associates the color with wood and/or nature.

The quality of lignin: The experts state that the heterogeneity of lignin leads to unpredictable and unreproducible properties of lignin-based composites, which is undesirable for commercial applications. The heterogeneous structure might also lead to weak interactions between some lignin compounds and the matrix, which can cause reduction of the performance (Doherty *et al.* 2011, Chen *et al.* 2014). The experts point out that this issue does not depend only on the raw material (e.g. the lignin source), it also strongly depends on the pulping process itself and impurities connected to this (types and amount) (Paulitsch and Barbu 2015). Therefore, efforts should be made to improve the quality of technical lignins after the extraction from the pulp mill. The experts report that additional processes and pretreatment technologies (e.g. fractionation), in order provide more uniform lignin compounds, are already under development. Besides, many experts also state that, although attempts were already made to improve the quality of lignin, there is still a lot of research needed to be able to use lignin as raw material in various composite applications. In order to support the market diffusion, it is necessary to improve the communication between the lignin

provider and the user by implementing e.g. quality indicators. Based on that, the provider should gain knowledge about the quality requirements of the lignin, and vice versa, the potential user can get information on the quality that can be provided by the pulp and paper industries.

The price of pretreated lignin: Regardless of the final application, the price of lignin as raw material plays a crucial role for the material use of lignin (Gabriel *et al.* 2017, Lettner *et al.* 2017). The experts state that the price of lignin can be seen as an incentive when using it to substitute petrochemical-based materials. In terms of using lignin as thermoplastic composite, the participating experts state that it is important to also integrate any kind of required pretreatments when assessing the price of lignin. Possible pretreatments (e.g. fractionation and purification steps) cause additional costs and thus the higher lignin price is seen as a potential barrier. Depending on the pulping process, different treatments are necessary and thus the knowledge about potential costs (Jönsson and Wallberg 2009, Tomani 2010) is still limited (Gabriel *et al.* 2017). Furthermore, the market price is determined by factors like the quality of lignin, process costs, production volume and costs for replacing energy lost due to lignin extraction, etc. (Gabriel *et al.* 2017). From low-purity lignin up to high-grade lignin, the price ranges between 40€/t for low purity lignin and 750 €/t for high-grade lignin (Gosselink 2011, Smolarski 2012, Hodásová *et al.* 2015). Furthermore, the experts state that the availability and the low price of petrochemical-based materials impedes the development of lignin-based composites.

The actual availability of lignin: In the literature, the availability of lignin is often seen as a main incentive. Each year, the pulp and paper industry produces 50 – 70 million tons of lignin worldwide (Lora and Glasser 2002, Gosselink *et al.* 2004, Kamm *et al.* 2008). It is noteworthy that some experts do not see this high availability in practice. Lignin should not be considered as waste stream, in fact it does have its intended use as energy source at the pulp mill. The experts furthermore mention that although the theoretical availability was always high, in practice it was not easy to get larger amounts of lignin. Two possible reasons are mentioned by the experts: firstly, the pulp mills as lignin providers still face a lot of uncertainties (e.g. costs of pretreatments, demand, acceptance price, etc.); secondly, although the accruing amounts of lignin are high, in the short-term only the lignin surplus (i.e. the amount of lignin that is not required for energy generation in the pulp mill) is seen as being available for material applications. It is also worth to mention that since the installation of extraction processes, e.g. LignoBoost at Stora Enso's Sunila mill (Finland) and at Domtar's Plymouth mill in North Carolina (USA), the availability of lignin has increased.

The lower technical properties of lignin-based thermoplastic composites: The experts frequently mention that with an increase in lignin content the performance of the composite decreases; for example, thin-walled injected WPC tends to break more easily and water uptake increased too (incl. lowering of dimensional stability) (Tudor *et al.* 2015). Taking into consideration that composites include a high variety of combination of materials and applications, it is not so easy to conclude that lignin decreased the technical properties in general. To summarize, studies have shown that tensile strength and elongation at break of PLA-lignin composites decrease and thermal degradation accelerates with a higher lignin content (Li *et al.* 2003). Nevertheless, the experts state that with further research and development, the technical properties will improve and/or the lignin content can be increased without losses in performance.

2. Incentives for the market diffusion of lignin-based composites

Besides the barriers of a market diffusion of lignin-based composites, the aim was to identify potential incentives that can support the market diffusion. According to the participating experts, the main incentives include:

The contribution to bio-economy: The general idea of using lignin as bio-based material for material applications matches the concept of bio-economy. One key-factor is the reduction of greenhouse gases, which could be achieved by substituting petrochemical-based raw materials (Langeveld and Sanders 2010). Many participating experts state that the bio-based, renewable and sustainable character of lignin as raw material is a main incentive for using lignin in composite materials. Compared to some other bio-based materials, the experts see a major advantage in the use of lignin, because it does not compete with food production.

The environmental advantages: Several experts mention that lignin-based composites provide environmental advantages compared to petrochemical-based products. The environmental advantages could result in a growing market demand for lignin-based composites. This could lead to an increased interest of composite producers who are expecting a competitive advantage of their products. Furthermore, the experts mention that the potential environmental advantages might also encourage the pulp and paper

industry to support the material use. The question of how to account for these potential environmental benefits and how to conduct environmental assessments for emerging technologies and products is still under development (Hesser *et al.* 2016, Suter *et al.* 2016, Lindner *et al.* 2017, Olsson *et al.* 2017, Lettner *et al.* 2018).

The inexpensive raw material: The literature on lignin as raw material presents the potential lower price compared to petrochemical-based counterparts as a main incentive (Stern *et al.* 2012). As already mentioned above, the actual price of lignin strongly depends on the quality of lignin. The experts state that for a material substitution the raw material price of the substitute is an important factor for a successful market diffusion. Considering lignin as substitution material for petrochemical-based materials, several experts attribute a cost advantage. Another incentive several experts mention is that, compared to petrochemical-based raw materials, the stability of lignin prices is assumed. The conducted interviews further reveal that the experts see the influence of this factor especially for industrial products (e.g. packaging, technical parts, construction, etc.) and not for products provided to the end-consumer (e.g. toys or household items, etc.).

The availability of lignin as raw material: The availability of lignin as a by-product from pulp and paper mills is frequently mentioned as a main incentive in the expert interviews. The experts furthermore state that, besides the large quantities available, it is (compared to other bio-based materials) noteworthy that another benefit is that lignin is an almost world-wide and year-round available raw material. Therefore, it can be assumed that downstream sectors can also achieve a stable production. Furthermore, some experts mention that potential energy trade-offs within the pulp mill resulting from an increase in material use have to be considered.

The improved strength of lignin-based thermoplastic composites: Found in the cell wall of woody plants, lignin is responsible for several functions: e.g. to serve as a structural material by providing strength and rigidity. Additional to the mechanical support, lignin fulfills a protective function as its heterogeneous nature enhances the resistance to degradation by most microorganisms (Haghdan *et al.* 2016). Studies have shown that, by incorporating lignin, the final composites and blends can have improved strength or elongation at break (Wang *et al.* 1992, Simionescu *et al.* 1996). The experts state that, as a result of the lignin structure, it is a suitable raw material for applications requiring high strength and thus is theoretically feasible for the production of composites. The experts also mention that in line with the quality variations of lignin the final properties of the lignin-based composite can vary greatly and there through being not attractive for a commercial application (Tudor *et al.* 2015).

3. Market development and bottlenecks along the value chain

The presented study also includes the issue of **potential factors influencing the market development** in order to gain information on future markets for lignin and lignin-based composites. In general, the participating experts predict a positive market development for lignin-based products, but also state the difficulties and uncertainties regarding the development (e.g. policy and/or price changes). The conducted interviews also reveal that the experts see the kraft process as more suitable for further processing compared to the sulfite process. Still, the experts frequently mention that there is a gap between the theoretical and the actual availability of kraft lignin for material use, leading to uncertainties and even wrong expectations. The experts state that, in term of lignosulfonates, although the availability is given, there are already applications for lignosulfonates, thus using lignosulfonates for composites would not only require additional treatment steps, but it would also lead to trade-offs between various material usage possibilities. Although it seems that the previously mentioned barriers are surmountable with further research and development (e.g. development of inexpensive valorisation technologies), it is noteworthy that the experts mention that the most suitable application for lignin has not been found yet and further research will be necessary.

In order to increase knowledge about the lignin value chain, it was also interesting where the experts see current **barriers** for the market diffusion. In line with the above-mentioned main barriers of lignin as raw material, it could be observed that the experts see the pulp and paper industry as the decisive stakeholder. The issue of innovation in forest-based industries has already been discussed in literature (Crespell *et al.* 2006, Björkdahl *et al.* 2011, Roos *et al.* 2014). The experts also state that in order to overcome potential bottlenecks along the value chain it is important to debunk the myth that lignin is a waste product and thus for free. One common message from the group of researchers is that to foster the market diffusion it is necessary to create new inter-organizational value chains from raw material to final applications. It is also noteworthy that the market diffusion of lignin-based composites does not rely only on the pulp and paper industries. Since the key-factors influencing the market diffusion of lignin as raw material are diverse (Lettner

et al. 2017), the expert interviews reveal the high interdependences between the various stakeholder groups and the need for cross-sectoral networks. Considering the potential consumer, the conducted interviews also show that this stakeholder group does not primarily ask for lignin as raw material, they are in general interested in increasing their bio-based product portfolio. Thus, it can be assumed that lignin as raw material does not only compete with petrochemical-based raw materials, but also with other bio-based materials (e.g. polylactic acid, starch, etc.). Besides the included stakeholder groups, the experts also frequently mention that the role of the end-consumer (i.e. by requesting bio-/lignin-based products) and the role of policy (i.e. supporting and funding of lignin-related research) should not be underestimated or even neglected. The experts furthermore recommend improved interactions between the various stakeholder groups and transdisciplinary R&D projects in order to foster the market diffusion of lignin and lignin-based composites.

CONCLUSION

With regard to the barriers for the market diffusion of lignin-based thermoplastic composites, the potential odor nuisance, the usually darkish brown color and the poor technical properties, especially with a higher content of lignin, are mentioned frequently as limiting the potential application areas. According to the experts, there is a lot of ongoing research, e.g. development of pretreatment technologies, to overcome those barriers. Nevertheless, it is noteworthy that by applying additional pretreatments to the raw lignin, the price of lignin as raw material will increase, which would be, according to the experts, a barrier. Furthermore, without additional pretreatments, the market diffusion of lignin seems quite limited, because the constant quality of lignin which is required by composite producers cannot be assured at the moment. Considering the price of lignin, it is important that potential users of lignin as raw material understand the value of lignin as an energy source in pulp and paper industries. The expert interviews reveal that there is a disagreement regarding the price of lignin along the value chain. While the pulp and paper mills are looking for additional profits, potential lignin consumers are primarily looking for cheap alternatives for petrochemical materials and products. In terms of incentives, besides the expected environmental benefits and the availability of lignin, the potential additional profits for the pulp and paper industries are seen as the main incentives. Furthermore, the expected lower price of lignin and the given price stability of lignin compared to petrochemical-based materials could foster the market diffusion of lignin as raw material for various applications. The creation of industrial networks is considered as one possibility to overcome currently existing bottlenecks. Besides the improvement of cost-performance relations, sustainability and environmental issues are seen as drivers for the future market development for the implementation of lignin-based composites.

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