Deliverable report

D5.3 Report on detailed policy advice in order to remove non-technical deployment barriers

Deliverable Data		
Deliverable number	D5.3	
Dissemination level	LignoCOST	
Deliverable name	Report on detailed policy advice in order to remove non-technical deployment barriers	
Work package	WG5	
Lead WP/Deliverable beneficiary	Apostolis Koutinas	
Deliverable status		
Submitted (Author(s))	10/04/2023	Apostolis Koutinas
Verified (WP leader)	10/04/2023	Apostolis Koutinas
Approved (Coordinator)	24/04/2023	Richard Gosselink

Contents

Introduction **3**

Current deployment status of lignin-based products **3**

The need for policy development 4

Identification of important non-technical barriers **4**

Definition of categories 4

Description of barriers related to lignin-based value chains 5

Economy/Business/Market uptake 5

Innovation 6

Scale-up 6

Feedstock 6

Sustainability 7

Policy advice towards barriers overcome **7**

European targets 7

Policy advice for lignin-based value chains 8

Conclusions **9**

References **10**

Working Group 5

Introduction

Working group 5 intended to support the most promising lignin valorization chains via a multi-criteria evaluation of sustainability aspects. One of the main criteria was process profitability so as to achieve maximal use of lignin's market potential and support its market deployment. During LignoCOST, the non-technical deployment barriers were identified and strategies in order to overcome them were assessed. Techno-economic, environmental and social aspects were evaluated to justify the utilization of renewable resources for the production of bio-based products, as well as biorefinery development was applied for the improvement of the process efficiency and sustainability. Economic sustainability indicators were estimated to help convincing relevant stakeholders to focus on lignin valorization schemes. The potential development of large-scale production units, the evaluation of the time required to achieve technological maturity, market stability and expansion were also considered so as to compare the current status with the future potential and quantify the current gap for certain processes to reach the market. Finally, policy and legislation amendments were assessed to facilitate industrial implementation of novel lignin valorization technologies.

Deliverable 5.3 presents the current status on lignin-based value chains highlighting the necessity of appropriate policy development. The categories of the non-technical barriers have been identified. Finally, policy recommendations have been made based on the European targets related to the circular bioeconomy.

Current deployment status of lignin-based products

Lignin is a naturally occurring material that is widely available on Earth and it is primarily produced as a byproduct of paper and ethanol production. The annual global production of lignin is around 100 million t, valued at $732.7 million in 2015, and it is projected to reach $913.1 million by 2025 with a compound annual growth rate of 2.2%. The three main categories of lignin are lignosulphonate, Kraft lignins and organosolv, with the latter showing the highest growth potential due to bioethanol production (Bajwa et al., 2019).

There is a growing demand for lignin as a replacement of fossil-based phenols in resins for wood-based panel applications (Hemmilä et al., 2017), as a binder (Bryntesen et al., 2023), adhesive (Khan et al., 2019), as a re-inforcement for bioplastic production (Yang et al., 2019), concrete admixture (Bajwa et al., 2019), in biomedical applications (Domínguez-Robles et al., 2020), in smart material production (Moreno & Sipponen, 2020), in cosmetics (Widsten, 2020) as well as for other applications (Nasrullah et al., 2017). The development of upstream and downstream valorization techniques will refine lignin as a building block for high-value chemicals. The researcher's interest is also depicted through the number of publications related to the valorization of lignin, which has been increasing over the years. Before 2008, only six papers were published, but after that year, the number of publications rapidly increased. In 2016, 108 papers were published, indicating an exponential growth trend. This exponential trend is in contrast to research on hemicellulose valorization, which showed a linear growth rate. This suggests that the investigation on lignin valorization has gained more specific interest in recent years and has become a popular research topic in the field of lignocellulosic biomass biorefineries. Maximum research output is based on the elucidation of lignin structure, recovery, and characterization of lignin, as well as lignin depolymerization by thermochemical and biological methods towards lignin applications (Abejón et al., 2018).

One of the biggest challenges associated with lignin utilization is the complex and heterogeneous nature of lignin. The complexity of lignins chemical structure makes it difficult to process and convert into useful products and thus a pretreatment stage is necessary. Another challenge is that lignin tends to repolymerize

after depolymerization, making it difficult to break the bonds formed by recondensation. Hydrogenolysis and recondensation processes often occur simultaneously during depolymerization. This can make it difficult to stabilize and store lignin for later use. Despite the increasing research focus, the industrial use of lignin is still limited. However, products derived from lignin have demonstrated their potential environmental benefits (Abu-Omar et al., 2021).

The need for policy development

In order for lignin-derived products to be discharged from the non-technical barriers that stand in the way of their full acceptance in the global marketplace, focus must be directed to the following issues.

First, a clear regulatory framework must be established. This is necessary to provide guidance to the industry and to ensure that lignin-derived products comply with safety and environmental regulations. Regulators should work with industry stakeholders to develop a regulatory framework that takes into account the unique properties of lignin and ensures the safety and sustainability of its use. For example, lignin has the potential to serve as an eco-friendly supplement that not only enhances the mechanical and gas barrier characteristics of polymer films, but also offers antioxidant and anti-UV properties (Boarino & Klok, 2023). Today there are no specific regulations that advocate or discourage the use of lignin-derived products in the food market. On the other hand, these products must comply with regulations governing the use of materials in food packaging. In the United States, the Food and Drug Administration (FDA) regulates the use of food packaging materials under the Federal Food, Drug, and Cosmetic Act (FD&C Act) and related regulations. Any new food packaging material, including those derived from lignin, would be required to undergo premarket review by the FDA to ensure its safety for use in food contact applications (Federal Food, Drug, and Cosmetic Act (FD&C Act) | FDA, n.d.). In the United States, lignin is generally recognized as safe (GRAS) for use in food packaging materials, but its use in food packaging is still limited. The European Union has its own regulations, such as the Framework Regulation (EC) No. 1935/2004 (Union Guidelines on Regulation (EU) No 10/2011 on Plastic Materials and Articles Intended to Come into Contact with Food Version History, 2013), that regulates the use of materials in contact with food.

Secondly, the use of lignin-derived products face economic feasibility problems, especially when compared to their fossil-based counterparts. This creates the need for financial incentives that can encourage investment in lignin-derived products and help to offset the high costs associated with research and development of sustainable and highly efficient lignin-derived products.

Finally, the acceptance of the general public on the use of lignin-based products should be promoted. Increasing public awareness of the benefits of lignin-derived products can help increase demand and encourage investment in the industry. Governments could launch public education campaigns to inform consumers about the benefits of lignin-derived products and their potential to reduce the environmental impact of conventional products.

Identification of important non-technical barriers

Definition of categories

To effectively address the challenges hindering the valorization of lignin, it is important to identify and categorize the non-technical barriers. Therefore, this study proposes the division of barriers into six different categories, namely Economy/Business/Market uptake, Innovation, Scale up of new technologies, Feedstock, Sustainability, and Policy and Regulation. This approach allows for a comprehensive analysis of barriers to lignin valorization and provides a structured approach to identifying key parameters that hinder lignin

commercialization. By dividing the barriers into these categories, this framework provides a clear understanding of the key non-technical factors affecting the full valorization of lignin.

The category "Economy/Business/Market uptake" encompasses financial barriers, market entry challenges, and comparison of prices and qualities to fossil counterparts. "Innovation" is related to investment and validation of new technologies and funding for collaborations between research, engineering/consulting and industry. "Scaling up new technologies" includes research and development of new products, financial support and validation at demonstration and pre-commercial scale. The "Feedstock" category addresses biomass availability and waste management. "Sustainability" considerations include techno-economic, environmental and social performance issues, end-of-life strategies and impacts on recyclability of waste streams. Finally, "Policy and Regulation" address the need for financial support, specific regulations and standards, stable and long-term regulations, and a competitive market to encourage the adoption of bio-based lignin-derived products. Table 1 presents a summary of the identified barriers as a starting point for further analysis and discussion.

Tabel 1 Non-technical barriers of lignin value-added products

Category of barrier	Definition
Economy/Business/Market uptake	Financial barriers related to multiple market entry and economic development. Prices and qualities comparison with fossil counterparts and Production costs
Innovation	Barriers related to investment for innovation and validation of new technologies. Funding collaboration between research, engineering teams and industry players.
Scale up of new technologies	Barriers related to research and development of new products and financial support for scale-up. Validation of new technologies at demonstration and pre-commercial scale.
Feedstock	Barriers related to feedstock availability and biomass supply chains
Sustainability	Barriers related to the evidence on the biobased products' sustainability considering techno-economic, environmental and social life cycle performance of relevant value chains. Building consumer confidence for bio-based products over fossil-based ones.

Description of barriers related to lignin-based value chains

Economy/Business/Market uptake

The annual production of lignosulfonates from sulphite pulping was around 1.8 million t in 2017, which counted for 90% of the total market of commercial lignin (Aro et al., 2017). The barriers for bio-based resins is that they compete with higher value-added products, which already have established markets and the production volumes in the pulp and paper sector are relatively small. Furthermore, large pulp and paper companies that are dominant in the lignin market, can offer the product at high quantities and low price, which present challenges for newcomers to enter the field (Mäki et al., 2021). The bio-based alternatives are not cost-competitive most of the time, while their performance on the final applications is lower.

The development of new bio-based products requires REACH (European Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals) registration. The difficulty of the whole enrollment process is high, especially for small and medium-sized enterprises (SMEs), which may not have the financial and technical support to complete the registration. Furthermore, lignin-based resins are not expected to offer significant economic developments, like offering new job positions.

Finally, the low cost competitiveness of the bio-based product versus fossil-based products should be pointed out, especially for drop-in chemicals or materials that do not offer additional functionalities. In this case the research and development needs are to decrease production cost either by improving the conversion processes or by trying to use low cost raw materials (e.g. switching to lower cost feedstocks).

Innovation

The need for research and development on the lignin-based resins is mandatory, although there is limited guidance and direction in R&D for the development of such processes. The environmental boundaries for such processes are not well understood, making their implementation more complex. A barrier that innovation faces is the successful diffusion of sustainable innovations, which is necessary for invigorating business' environmental and social goals while enhancing their economic performance (Dibrell et al., 2014). Intellectual property rights can also cause barriers for the development of new lignin-based products, due to patents, trademarks and copyrights that already exist.

Scale-up

Transformation to bio-economy increases the risks, costs and constraints in doing business. The scale-up of new bio-based products is a challenging process, as it requires a high level of investment, new technologies development and market risk. All the above factors increase the financial investment required, especially at the transition of pilot plants to sub-commercial plants.

There is a limited number of facilities with high TRL technologies in the lignin-based products pathways. The development of high TRL technologies entails the design, building and operation of the plants themselves, which requires time and expertise in the specific field. Academic research teams have lack of engineering knowledge on the scale-up requirements, making impossible the progress of high TRL technologies. The TRL scale is strongly related to the required funding (Weber et al., 2012). Lignin-based products are subjected to the typical problems that start-ups have, such as difficulties in finding investment for new plants construction. Due to its innovative character, it requires pre-feasibility studies on the level of feedstock, technology and process development. These actions can be expensive, as resources in multiple fields are required. The capital and operating cost for such investments can be high, due to an earlier stage of technological development, compared to the fossil-derived products. The difficulty of optimization and validation of such new technologies at demonstration and pre-commercial scale, coupled with the market risk, hinder financing.

Another barrier that lignin-based products are facing is the biomass availability and quality required for scale-up. Lignin production from renewable resources has not been optimized properly so far, thus there are high losses during the whole process. A hurdle to the scale-up of lignin production that also needs to be highlighted is the generation of the residual streams. High amounts of organic and inorganic components are produced as waste streams, which need further processing.

Feedstock

To address concerns about biomass supply potential, funding is needed for consistent regional and local biomass resource assessments that include all feedstock types. Further research and information on the potential of biomass resources across Europe, including identification of high feedstock density or high

potential areas, and especially sources that have low competition with food/feed, is also needed so that overall regional potential and impacts can be assessed along with other biomass uses. The establishment of biomass and waste supply companies can also be supported, which would work with technology developers and/or resource holders to identify suitable sites and ensure feedstock supply and quality to serve the bio-based product, fuel and energy industries.

It is critical to ensure stable supply prior to plant construction, as finding plant locations based on feedstock availability can be time-consuming and difficult, especially when competing with other requirements. All biomass feedstocks have resource constraints in the medium term, and this lack of clarity about limits is a barrier to governmental action and investor confidence in bioproducts (Platt et al., 2021)

In addition, it is important to consider crops for biorefineries when considering the regulation of GM crops in general, to establish whether there are opportunities with acceptably low risks. To address the problem of inconsistent classification of materials as waste, residue or coproduct, clearer definitions and guidelines for these terms should be established through collaboration between national and international regulators and industry stakeholders. Greater transparency and traceability throughout the supply chain can also help ensure that materials are correctly classified and potential loopholes are identified and addressed.

Sustainability

The primary advantage of bio-based chemicals and materials is that they should be environmentally friendly (such as GHG emissions reductions). These advantages must be evaluated and widely understood before they can be valued. There is a lack of evidence on the sustainability advantages of bio-based products, including the lignin-based ones. Every bio-based product requires sustainability information in order to demonstrate value and minimize negative consequences to the environment. Depending on the feedstocks and methods employed, certain bio-based products may have minimal GHG reductions or even GHG rises when compared to fossil-derived products.

Case studies identified uncertainty about the environmental performance of case-specific bio-based products. Moreover, there are concerns about the impact of bio-based goods on waste stream recyclability and the lack of visibility of the benefits of bio-based products. The concept of “bio-based” is perceived as poor marketing term. Some consumers connect the term "bio-based" with inferior quality and/or greater pricing. Being bio-based is no longer a totally convincing sales justification for producers, consumers and certain policymakers and the terminology that is used may be confusing.

Overall, the sustainability of lignin innovations should be evaluated on a case-by-case basis, because the processes, approaches and assumptions (e.g., system boundaries and allocation approaches used) are highly specific to each case and, as a result, can influence the outcome of such studies. Sustainable methods offer the potential to identify environmental hotspots and enhance decision-making for sustainable processes and products throughout the innovation process (Platt et al., 2021).

Policy advice towards barriers overcome

European targets

Nowadays, to promote a bioeconomy based on renewable resources, the European Union has adopted various strategies to make economic processes and products more sustainable, with expected contributions to a number of policy goals.

In this context, the European Union has set out a number of policy initiatives with the overarching goal of making Europe climate neutral by 2050, under the name European Green Deal. As part of the EU Green Deal,

the following policy initiatives can be considered relevant to the use of lignin-based products and their market potential, as they would drive and reward the development of sustainable bio-based products.

1. **European climate law** aimed at reducing CO_2 emissions while promoting a circular economy and reducing chemical pollution.
   A. Carbon Border Adjustment Mechanism (CBAM): Non-EU trading partners that meet less stringent emission limits would pay a carbon tax when they bring products to the EU market.
   B. Just transition fund is a new financial instrument under cohesion policy supports regions in the transition towards climate neutrality by 2050. The mechanism of just transition fund should focus on the regions and sectors most affected by the transition due to their dependence on fossil fuels and make agriculture more sustainable.
   C. Circular Economy Action Plan is set to promote waste prevention and the circular economy and to prioritize funding for the implementation of the Bioeconomy Strategy.
   D. Chemicals Strategy for Sustainability aims to drive innovation by promoting the use of safer and more sustainable chemicals instead of hazardous chemicals, while protecting EU citizens and subsequently the environment. (https://echa.europa.eu/hot-topics/chemicals-strategy-for-sustainibility)
2. **Renewable Energy Directive II (RED II):** defines a set of sustainability and greenhouse gas emission criteria that liquid biofuels in transport must meet.
3. **Waste Framework Directive (WFD):** The aim of this is to improve waste management systems in terms of sustainable materials, to increase the efficiency of resource use and to ensure that waste is valued as a resource.
4. **Registration, Evaluation, Authorization and Restriction of Chemicals (REACH):** is a regulation that address the intrinsic properties of chemical substances in order to improve the protection of human health and environment (reference).

EU legislations, such as the European Green Deal, RED II, WFD and REACH is expected to be beneficial for bio-based products production, including lignin-based ones. Policy and regulations must be developed and implemented in order to bring the benefits in EU and subsequent support in the production of bio-based chemicals and materials and overcome the identified barriers.

A carbon tax on fossil alternatives should be implemented, making bio-based products from alternative renewable sources more competitive. Clear regulations, standards and product approval procedures for bio-based products should be developed to support the growth of the bio-based market.

Policy advice for lignin-based value chains

Scientific groups specialized in lignin valorization highlight the necessity for appropriate policy establishment and development of a specific framework that should be followed in order to achieve the desired market growth of lignin-based products. For example, Hall et al. (2018) reported the production of vanillin and carbon fibers utilizing lignin as raw material. The costs for these new technologies related to regulatory approval, labeling and trade policies counterbalanced the improved price performance of such products. The main conclusion of this study was that labeling was a significant problem in the case of Canadian vanillin derived from lignin, and that the usage of carbon fibers faced significant difficulties in terms of trade restriction rules and regulatory approval in the USA. Lettner et al. (2020) performed an importance-performance analysis to examine the knowledge gaps (information asymmetries) between various stakeholder groups regarding Kraft lignin based phenol-formaldehyde (PF) resins for wood-based panels and lignin-based polyurethane (PU) resins for PU foams. Through cross-sectoral cooperation and increased communication, a common framework for the comparison of bio-based and conventional products and

fresh cooperation among stakeholders along the entire value chain, information asymmetries can be reduced.

The success of commercial lignocellulose biorefineries and marketable lignin-based products depends on reducing capital and operational expenses while maximizing the use of lignin for the production of value-added products. Other than solving the technical parameters, the confrontation of the non-technical parameters such as the regulatory framework, the economic feasibility problems, and the general public acceptance is also imperative. It is important to establish appropriate policies for lignin refinement and the production of fuels and chemicals in lignocellulose biorefineries. These policies should focus on exploring meaningful lignin applications that safeguard the environment and provide financial benefits to paper mills, lignocellulosic biorefineries and other manufacturing industries (Garlapati et al., 2020).

A robust policy framework will be essential for achieving energy gains, promoting a circular economy, reducing carbon emissions and preserving biodiversity. To encourage industry to produce more lignin-based products, it is necessary to continue investigating cost-effective lignin valorization technologies. Techniques like process design, techno-economic evaluation and life cycle assessment can be useful in identifying the benefits and challenges associated with scaling up the production of lignin-based products and taking lignin valorization technology from the initial stage to the next level. Developing and designing lignin valorization methods based on eco-friendly principles will contribute to the growth of an integrated biorefinery industry and also enhance the profitability of existing pulp and paper industries (Bajwa et al., 2019).

The availability of lignin can be increased through policies that promote the development of second-generation biorefineries. Subsidies that increase the competitiveness of the development of materials from these biorefineries can further enhance this. In addition, lignin is used in these plants as a biofuel for energy recovery, and it is essential to ensure that these plants can continue to use this energy from biomass even if a solution for lignin use is developed on a larger scale. In addition to these drivers, REACH acts as a driving force to replace substances of particular concern with less harmful substances and to adhere to green chemistry principles.

Policy related to the EU targets and the lignin-based value chains should be developed in order to overcome the non-technical barriers, presented in the previous section, and achieve market growth. This set of policies should not only be developed for this sector but also in accordance with policy changes that may influence the deployment rates of other bioeconomy sectors. Policy developments will help determine the overall and relative ramp-up of the bioeconomy era.

Conclusions

To address the lack of financial support for lignin-based products, proposing specific regulations and standards could be a solution. Such regulations could ensure the environmental and social sustainability of the products and provide clear guidelines for their use to increase market acceptance and use. Another possible solution is to establish stable and long-term regulations that provide certainty for investors, including tax incentives, grants and other financial support mechanisms that encourage investment in lignin-based products. To make them competitive in the marketplace, production costs must be reduced and product quality improved through the use of innovative technologies and greater collaboration between industry and academic research. Finally, policies for bio-based products, such as research and development funding, regulatory support and public procurement policies that prioritize the use of bio-based products, can promote the development of lignin-based products and accelerate the transition to a more sustainable and bio-based economy.

References

Abejón, R., Pérez-Acebo, H., & Clavijo, L. (2018). Alternatives for Chemical and Biochemical Lignin Valorization: Hot Topics from a Bibliometric Analysis of the Research Published During the 2000–2016 Period. Processes 2018, Vol. 6, Page 98, 6(8), 98. https://doi.org/10.3390/PR6080098

Abu-Omar, M. M., Barta, K., Beckham, G. T., Luterbacher, J. S., Ralph, J., Rinaldi, R., Román-Leshkov, Y., Samec, J. S. M., Sels, B. F., & Wang, F. (2021). Guidelines for performing lignin-first biorefining. Energy & Environmental Science, 14(1), 262–292. https://doi.org/10.1039/D0EE02870C

Aro, T., & Fatehi, P. (2017). Production and application of lignosulfonates and sulfonated lignin. ChemSusChem, 10(9), 1861-1877.

Bajwa, D. S., Pourhashem, G., Ullah, A. H., & Bajwa, S. G. (2019). A concise review of current lignin production, applications, products and their environmental impact. Industrial Crops and Products, 139, 111526. https://doi.org/10.1016/J.INDCROP.2019.111526

Bryntesen, S. N., Tolstorebrov, I., Svensson, A. M., Shearing, P., Lamb, J. J., & Burheim, O. S. (2023). Introducing lignin as a binder material for the aqueous production of NMC111 cathodes for Li-ion batteries. Materials Advances, 4(2), 523–541. https://doi.org/10.1039/D2MA00850E

Demirbas, M. F. (2009). Biorefineries for biofuel upgrading: a critical review. Applied energy, 86, S151-S161.

Dibrell, C., B Craig, J., Kim, J., & J Johnson, A. (2015). Establishing how natural environmental competency, organizational social consciousness, and innovativeness relate. Journal of Business Ethics, 127, 591-605.

Domínguez-Robles, J., Cárcamo-Martínez, Á., Stewart, S. A., Donnelly, R. F., Larrañeta, E., & Borrega, M. (2020). Lignin for pharmaceutical and biomedical applications – Could this become a reality? Sustainable Chemistry and Pharmacy, 18, 100320. https://doi.org/10.1016/J.SCP.2020.100320

Garlapati, V. K., Chandel, A. K., Kumar, S. P. J., Sharma, S., Sevda, S., Ingle, A. P., & Pant, D. (2020). Circular economy aspects of lignin: Towards a lignocellulose biorefinery. Renewable and Sustainable Energy Reviews, 130. https://doi.org/10.1016/j.rser.2020.109977

Hall J, Matos S, Gold S, Severino LS. The paradox of sustainable innovation: the 'Eroom' effect (Moore's law backwards). J Clean Prod. 2018;172:3487–97. https://doi.org/10.1016/j.jclepro.2017. 07.162.

Hemmilä, V., Adamopoulos, S., Karlsson, O., & Kumar, A. (2017). Development of sustainable bio-adhesives for engineered wood panels – A Review. RSC Advances, 7(61), 38604–38630. https://doi.org/10.1039/C7RA06598A

Khan, T. A., Lee, J. H., & Kim, H. J. (2019). Lignin-Based Adhesives and Coatings. Lignocellulose for Future Bioeconomy, 153–206. https://doi.org/10.1016/B978-0-12-816354-2.00009-8

Lettner M, Hesser F, Hedeler B, Schwarzbauer P, Stern T. Barriers and incentives for the use of lignin-based resins: results of a comparative importance performance analysis. J Clean Prod. 2020;256. https://doi.org/10.1016/j.jclepro.2020.120520 Wenger et al., Curr Forestry Rep (2020) 6:294–308

Mäki, E., Saastamoinen, H., Melin, K., Matschegg, D., & Pihkola, H. (2021). Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: A review. Biomass and Bioenergy, 148, 106036.

Moreno, A., & Sipponen, M. H. (2020). Lignin-based smart materials: a roadmap to processing and synthesis for current and future applications. Materials Horizons, 7(9), 2237–2257. https://doi.org/10.1039/D0MH00798F

Nasrullah, A., Bhat, A. H., Sada Khan, A., & Ajab, H. (2017). Comprehensive approach on the structure, production, processing, and application of lignin. Lignocellulosic Fibre and Biomass-Based Composite

Materials: Processing, Properties and Applications, 165–178. https://doi.org/10.1016/B978-0-08-100959-8.00009-3

Platt, R., Bauen, A., Reumerman, P., Geier, C., van Ree, R., Gürsel, I. V., ... & Annevelink, E. (2021). EU Biorefinery Outlook to 2030 (Lot 3): Studies on support to research and innovation policy in the area of bio-based products and services.

Weber, J. (2012, October). WEC Technology Readiness and Performance Matrix–finding the best research technology development trajectory. In Proceedings of the 4th International Conference on Ocean Energy, Dublin, Ireland (Vol. 17).

Widsten, P. (2020). Lignin-Based Sunscreens—State-of-the-Art, Prospects and Challenges. Cosmetics 2020, Vol. 7, Page 85, 7(4), 85. https://doi.org/10.3390/COSMETICS7040085

Yang, J., Ching, Y. C., & Chuah, C. H. (2019). Applications of Lignocellulosic Fibers and Lignin in Bioplastics: A Review. Polymers, 11(5). https://doi.org/10.3390/POLYM11050751