After Decades of Extensive Research, Is Kraft Lignin Valorization Still Up In The Air? – Obstacles, Opportunities, and Myths

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In the past decades, substantial research efforts have been directed towards increasing the availability of renewable and recycled raw materials. Lignin, one of the most abundant natural polymers, constitutes a vast, renewable, and largely untapped source of aromatic structures. In addition, it is one of the most abundant renewable sources of carbon. Despite the countless research projects aimed at valorizing kraft lignin, the largest source of industrial lignin, relatively few commercial kraft lignin products have emerged. Simultaneously, lignosulfonates represent a commercially successful range of products with a steady and growing global market. This paper reviews the current outlook of technical lignin research, including common misunderstandings, and discusses various factors that have hampered the use of lignin as a renewable source of materials and chemicals.

DOI: 10.15376/biores.20.3.5218-5221

Keywords: Kraft lignin; Valorization; Lignocellulose; Lignin research; Myths

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A Brief History of Kraft Lignin Research

Like many fields, lignocellulosic science follows trends. In the 1990s, research focused on minimum-effluent mills, while the 2000s saw a shift to nanocellulose applications. More recently, lignin has become a major focus, attracting generous funding for its valorization. Conferences now feature numerous presentations on engineering lignin and its potential uses, from nanoparticles to batteries. The fascination with lignin is understandable.

Lignin is a unique biopolymer in biochemistry because it is racemic, composed of monomers linked by multiple types of bonds, such that it lacks a well-defined primary structure. It plays essential biological roles in plants by waterproofing vascular tissues, providing stiffness to wood, and, most importantly, protecting the polysaccharides in wood from rapid microbial degradation. Lignin is also very abundant, typically making up 20 to 30% of the dry weight of wood. It is often cited as one of the three most abundant biopolymers, along with cellulose and chitin. Although large amounts of kraft lignin can potentially be extracted from black liquor (Henriksson 2017), the annual production of lignosulfonates is limited to approximately 2 million tons. This limitation is due to the limited capacity of existing sulfite pulp mills (FAO 2022) and the lack of projects to expand sulfite pulping capacity.

Investment in kraft lignin research has increased significantly due to its potential as a renewable alternative to fossil-based materials (Yao *et al.* 2022). While exact global figures are unclear, major funding sources include the U.S. Department of Energy, Natural Resources Canada, the European Union, and several Asian and South American countries. Support is largely driven by the pulp and paper industry and environmental regulations, and it is expected to continue to grow as demand for sustainable materials increases.

To quantify lignin research output, we analyzed publications and patents using Web of Science and Espacenet. Our search included the keywords "lignin" and "lignosul*" to capture all technical lignin studies, especially review articles. Although various lignin sources exist, industrial-scale valorization will rely primarily on kraft lignin due to its vast untapped potential, while other sources remain marginal.

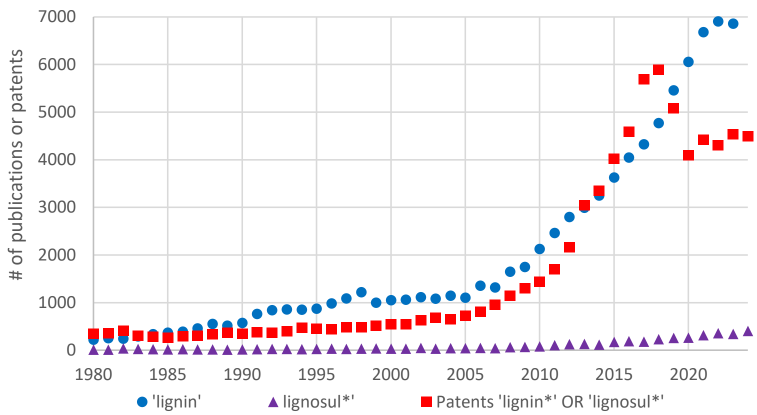

Fig. 1. Results from a bibliographic and patent searches related to lignin

Figure 1 shows a sharp increase in lignin-related publications after 2005, with an almost sevenfold increase by the 2020s. Patents followed a similar trend, while lignosulfonate studies grew modestly but remained far fewer. However, both publications and patents appear to have peaked around 2022. Most research has been focused on chemistry and materials science, followed by biological applications, environmental issues, and energy. Whether interest will decline or stabilize remains uncertain. The peak of lignin research may have passed, and future studies are likely to focus on the most promising applications.

Busting Myths about Lignin

Given the great scientific and economic interest in lignin, it is not surprising that several "myths" about lignin valorization have emerged over the past few decades, both from those who believe in the undeniable potential of lignin and from those who are skeptical about its technical viability. We will now discuss some of these myths:

"You can make anything out of lignin, except money". The pulp and paper industry has long viewed the heterogeneity of lignin as a barrier to commercialization (Wenger *et al.* 2020). However, lignin-based products can be highly profitable. Lignosulfonates (LS) have diverse applications, and Borregaard reported an average price of more than EUR 1,000 per ton in 2023 (Borregaard 2024). While dissolving pulp is typically the most valuable sulfite mill product, LS production significantly increases profitability and can sometimes generate more revenue than pulp.

"Great ideas equal great businesses". It is obvious that ideas that are not commercialized properly will not make money. The kraft pulping industry is among the most capital-intensive businesses, which in turn requires very high-capacity utilization rates. The difference between profit and loss typically occurs within the last narrow fraction of production. This leads to a situation where the management is unwilling to risk any part of their production by investing into something that involves great uncertainty and unpredictability.

"Cheaper products are always the best". The very difficult task of undercutting the competing products is not the only route to the market for lignin-based products and materials. Customers consider factors other than just price, including sustainability and environmental credentials. Therefore there can be a decent premium for lignin-based materials over the prices of the conventional materials made of fossil raw materials.

"It is best to start with high-value applications". This opposite statement is also problematic; lignin is a heterogeneous material, which generally poses challenges for demanding chemical applications. Its interesting properties, such as aromatic functionality, can easily be obtained from polymers synthesized by bio-based platform chemicals such as ethanol and furfural (Sun and Wang 2014; Kabbour and Luque 2020). High-value applications are also typically produced in relatively small volumes. Thus, the most realistic applications for lignin are those where its structure does not need to be very well-defined, and where large volumes are used—*i.e*., industrial bulk uses.

"Technical lignin that resembles natural lignin is more valuable". Lignin that is available in large quantities consists of various grades of technical lignin, which differ considerably from 'natural lignin' – *i.e.*, the biopolymer that is an integrated part of the wood structure. For a long time, some scientists have tried to prepare lignin as similar as possible to natural lignin structure in so-called 'lignin first-processes'. However, there are hardly any facts to substantiate that such lignin structures are significantly better than kraft lignin or lignosulfonates for most applications. It is important to note that the function of lignin in wood to add strength and stiffness is probably dependent of lignin-carbohydrate complexes, which are difficult to re-create artificially. In other words – one does not obtain 'wood' just by adding lignin to cellulose and hemicellulose!

"Lignin is a waste product from chemical pulping". The idea that large quantities of technical lignin can be obtained cheaply from chemical pulp mills is a misconception. In sulfite pulping, lignosulfonates are a valuable by-product, while in kraft pulping, lignin is burned for energy and chemical recovery, which is essential for mill operations (Hart 2011). Extracting up to 25% of lignin from black liquor is possible, but it is complex and risks disrupting the mill's chemical balance. Decades ago, Westvaco (now Ingevity) commercially produced kraft lignin for specialty lignosulfonates. More recently, large-scale processes such as LignoBoost (Valmet), Lignarec (Andritz), and CleanFlow Black have emerged.

"Lignin is a biopolymer ideal for consumer products". Replacing petroleum-based plastics with biopolymers is attractive because of their biodegradability and biocompatibility. Unlike synthetic polymers, biopolymers degrade naturally, with the exception of lignin. Its poor biodegradability slows decomposition, and humus is largely composed of partially degraded lignin. While natural lignin is not a microplastic and has been present in ecosystems for millions of years, engineered and chemically modified lignins differ significantly. Highly hydrophobic lignin derivatives could pose environmental risks. Another challenge is the strong odor of kraft lignin, which is a major drawback for consumer products, although some methods exist to mitigate it.

Concluding Remarks

So what should we use lignin for? There are two main sources of lignin: lignosulfonates and lignin from alkaline pulping. Lignosulfonates have a well-established market and new applications are emerging. However, their availability is limited, as sulfite mills struggle to compete with kraft mills. A potential alternative is oxlignin, which is intensely oxidized lignin from oxygen delignification stages of kraft pulp mills (Smyk *et al*. 2024). It has a high molecular weight and good solubility, but its large-scale production and effectiveness as a dispersant remain uncertain. Kraft lignin is structurally complex due to reactions during pulping. Recent evidence suggests that some of what we call "kraft lignin" may actually be aromatic polymers derived from polysaccharides. Despite this complexity, kraft and soda lignin can be produced in large quantities at low cost. Given these factors, bulk applications are the most logical for kraft lignin. Potential applications include binders such as bitumen in asphalt, polymer fillers and board adhesives, and fuels. Similar to petroleum tar and tall oil pitch, large-scale applications remain the best opportunity for kraft lignin.

References Cited

Borregaard Annual Report 2023. (2024). Borregaard ASA. Sarpsborg, Norway. 147 pp.

Food and Agriculture Organization of the United Nations (FAO). (2022). "Pulp and paper capacities, survey 2021–2026," Rome 2022. 208 pp. DOI: 10.4060/cc1985t

Hart, P. W. (2011). "The chemical versus energy cost tug of war: A pulp mill perspective," *Tappi J*, 10(7), 37-42.

Henriksson, G. (2017). "What are the biological functions of lignin and its complexation with carbohydrates?," *Nordic Pulp & Paper Research Journal* 32(4), 527-541. DOI: 10.3183/npprj-2017-32-04_p527-541_henriksson

Kabbour, M., and Luque, R. (2020). "Furfural as a platform chemical: From production to applications," *Biomass, Biofuels, Biochemicals*, 283-297. DOI: 10.1016/B978-0-444-64307-0.00010-X

Smyk, N., Sjöström, J., Henriksson, G., and Sevastyanova, O. (2024). "UV–vis spectroscopy as a rapid method for evaluation of total phenolic hydroxyl structures in lignin," *Nordic Pulp & Paper Research Journal* 39(4), 731-746. DOI: 10.1515/npprj-2023-0095

Sun, J., and Wang, Y. (2014). "Recent advances in catalytic conversion of ethanol to chemicals," *ACS Catalysis* 4(4), 1078-1090. DOI: 10.1021/cs4011343

Wenger, J., Haas, V., and Stern, T. (2020). "Why can we make anything from lignin except money? Towards a broader economic perspective in lignin research," *Curr. For. Rep.* 6, 294-308. DOI: 10.1007/s40725-020-00126-3

Yao, H., Wang, Y., Liu, J., Xu, M., Ma, P., Ji, J., and You, Z. (2022). "Review on applications of lignin in pavement engineering: A recent survey," *Frontiers in Materials* 8, article 803524. DOI: 10.3389/fmats.2021.803524