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# Lignin's role in the beginning of the end of the fossil resources era: A panorama of lignin supply, economic and market potential

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Lignin, one of nature's promising biopolymers, has been extensively studied for its potential to support the transition to a less fossil-based economy. Despite evidence from both industry and academia on its various applications, the economic feasibility of lignin still requires further research. This review brings an updated overview of lignin supply and recent techno-economic analysis (TEA) of technical lignin applications. With the global production capacity for kraft lignin reaching 112 kt/year in 2023, there is growing interest in assessing the economic viability of lignin-based products. Besides evaluating technical and economic feasibility, the reviewed TEAs identify bottlenecks and help optimise the processes. They define potential actions (e.g., increase capacity, adjust price strategy, and reduction of lignin cost) that could improve the feasibility of the developed lignin applications.

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## Introduction

Aromatic compounds, essential in everyday products, are mostly coming from fossil resources [1,2]. Moving away from fossil dependency requires circularity and the use of renewable bio-based resources. Lignin, a component of lignocellulosic biomass (LB) has the potential to be part of the solution. Lignin's abundance, aromatic nature, chemical versatility, and functional groups make it a promising platform for applications in the fields of materials science, chemistry, and energy.

Lignin is available as a side stream of kraft pulping (KP) and other LB processes. Valorising kraft lignin (KL) could reduce fossil fuel dependency, support the green transition, and incentivise the development of competitive bio-based industries [3,4]. Moreover, valorising lignin instead of burning it promotes circular bioeconomy strategies, as it decouples economic growth from resource exploitation. Finland exemplifies this potential, which aims to double its bioeconomy share by 2035, considering forest-added-value products a way to support its goal.

Lignin has been studied for various applications, including thermosets, thermoplastics, high added-value chemicals (HAVCs), carbon fibres, nanoparticles, and biomedical applications (e.g. drug delivery systems, wound healing, and bone and tissue engineering), among others that are still under development [5–7]. From an industrial perspective, Stora Enso is using KL to make alternatives to the anode in sodium-ion and lithium-ion batteries known as Lignode® [8,9], and the commercial UPM BioPiva™ lignin, which can be used to replace fossil-based phenol in phenolic resins [10].

The business and scientific communities have acknowledged the potential of lignin. Although the industry faces challenges, such as the closure of Stora Enso's Sunila mill in Finland, the world's largest extracted capacity KL at 50,000 t/y using the LignoBoost process [11]. However, there are also expansions, such as Metsä Group's investment in a new lignin demo plant [12], or Södra's plan to become the largest KL producer by 2027 [13]. Research on lignin has tripled in the past decade, focusing mainly on its technical aspects [14]. Recent reviews on lignin's chemical structure, modification processes, and technical potential are available in several studies [7,15,16]. Most publications provide minimal information on the economics of lignin-derived products [17].

Scientific advancements in lignin applications are numerous; most remain at the laboratory scale, struggling to reach higher technology readiness levels (TRLs). Bio-based innovations that manage to move up the TRL often take over 15 years to reach the market [18]. This review calls the attention of industry, academia, and policymakers to the importance of understanding lignin's potential applications and their economic feasibility. We examined 27 peer-reviewed papers from 126 published between January 2022 and March 2024, focusing on the techno-economic analysis (TEA) of lignin applications. Additionally, we reviewed company reports and market publications to provide an overview of technical lignin's development, focusing on reviewing its availability and techno-economic feasibility.

## Supply of technical lignins

Technical lignin is the isolated lignin from biomass [19]. They are classified as lignosulphonates (LS), KL and soda lignin, which come from the sulphite, kraft, and soda pulping processes, respectively [19]. Hydrolysis lignin (HL) is a by-product of the hydrolysis process when producing cellulosic ethanol [20]. And organosolv lignin (OL) is produced using organic solvent processes [21].

KL is the largest available type of lignin [6], with a global estimate of 70 million tonnes (Mt)/y. The amount of lignin available depends on factors such as the black liquor (BL), species and product mix at the mill [6]. Some researchers have supported a 20 % potential KL extraction, while others suggest 40 % [6,22]. A 40 % scenario becomes more attractive when KL applications bring higher margins than pulp, compensating for challenges in the pulping process. It is also crucial to secure large new market volumes to significantly substitute or replace lignin in fossil-based products.

To reduce risk, the industry typically starts with the smallest capacity to validate the technical concept and applications before scaling up. KL commercial extraction faces capacity reductions (Table 1 see Stora Enso and West Fraser). It is unclear if this infrastructure will be installed in other mills and lignin will continue to be extracted. The information provided in Table 1 is not exhaustive and may underestimate the current capacity, as there's limited information available on mill capacity in Asia.

LS are the second-largest lignin supply [23], with Borregaard, the leading producer, estimating a global production of 900 kilometric tonnes of lignin dry solids (kmtds) in 2023 [23]. LS, with its colloidal properties, high molecular weight and water solubility [24,25], has gained market consolidation as binding and dispersing agents in animal feed pellets, flavours, fragrances, and chemical building blocks [23,25].

Other types of lignin have a smaller share in the market but are growing. In Leuna, Germany, a new UPM biomass biorefinery plant with a capacity of 220 kt/y will produce enzymatic hydrolysis lignin to replace carbon black and silica for the rubbery industry [36]. Tofani et al.́s review shows five pilot plants testing OL biorefining processes, with a capacity ranging from 500 to 1000 t/y, while Chempolis and Fortum in Finland are assessing scaling up [21].

Lignin production expansion faces various challenges from a supply and technology perspective. Technical lignin faces different challenges, some are highlighted here, and more information can be found in other reviews [6,14,37]. OL needs further optimisation in chemical recovery and energy efficiency to achieve commercial scale [21]. High ash content and lower purity limit LS's use in high-value applications. [37].

**Table 1**

**Overview of KL extraction/recovery capacity globally.**

| Company | Location | Capacity as reported | 2023 estimated capacity (kt/y) | Stage of operation | Ref. |
|---|---|---|---|---|---|
| Stora Enso | Finland | 50 kt/y | 0 | Commercial, not in operation | [11] |
| Ingevity | USA | 50 kt/y | 50 | Commercial | [26,27] |
| Domtar | USA | 25 kt/y | 25 | Commercial | [28] |
| Suzano | Brazil | 20 kt/y | 20 | Commercial | [29] |
| West Fraser | Canada | 10.5 kt/y | 10 | Commercial operation uncertainty after the sale | [30,31] |
| RISE | Sweden | 6-8 kt/y | 6 | Demo | [32] |
| Resolute | Canada | 50 ODkg/day | 0 | Pilot | [31] |
| Klabin | Brazil | 1 t/day | 0.3 | Demo | [33] |
| Metsä | Finland | 2 t/day | 0 | Demo, in construction, planned for 2024 | [34] |
| Mercer | Germany | 1 t/day | 0.3 | Demo | [35] |
| Södra | Sweden | Not available information | 0 | Commercial, planned to be in operation in 2027 | [13] |
| **Total** | | | 112 | | |

Notes: 1 tonne per day is assumed to be 0.3 kt/y. OD: oven-dried.

KLs vary depending on the recovery process and feedstock, with colour and odour being its main limiting factors [38].

Lignin's price, crucial when considered as a raw material, varies with purity, making it difficult to define an exact number. Literature and market list commercial KL prices between 220 and 650€/t [39,40]. LS prices range from 280 to 2500€/t, although the end of 2023 saw prices ranging from 230 to 650 €/t, depending on the location or supplier [39,41]. OL prices are less commonly reported due to the lack of commercial suppliers, but estimates range between 1100 and 1250 €/t [42].

Limited supply, tight demand and supply chain issues often discourage lignin adoption. However, EU regulations are pushing the pulp and paper industry to valorise all biomass side streams, reducing the pressure and promoting the development or redesign of sustainable, circular products [43,44]. Besides, upcycling lignin from energy to added-value applications and improving the forest sector's environmental profile are key growth drivers.

### Overview of techno-economic analysis (TEA)

To advance in TRL, new lignin-based applications must prove technical and economic feasibility, making early-stage TEAs essential. Table 2 shows recent TEAs for technical lignins being valorised in applications beyond just purification or combustion for energy (without any modification).

Most TEAs focus on the biorefinery concept using agricultural, forestry residues, or industry-side streams, contributing to cascade use [45–49]. Biorefineries traditionally produce ethanol from cellulose and hemicellulose, with lignin used for electricity production. However, the studies in Table 2 emphasise that valorising lignin increases production cost, but it also brings higher economic value, compensating for the costs [45,50–52]. The concept of lignin-first is emerging, prioritising lignin over other biomass components inbiorefinery design rather than treating it as a byproduct [48,53,54]. Studies found this approach economically feasible, achieving a minimum selling price (MSP) competitive with existing fossil alternatives, with potential improvements by increasing biorefinery capacity and optimising the process [48,53].

Most of the studies in Table 2 are at the early stages, with low TRLs, with the highest being at level 7 [48]; therefore, achieving commercialisation requires significant time and effort. For biorefinery processes, lignin is primarily valorised for chemicals such as adipic acid (ADA), obtained through fermentation to replace the commercial one produced from cyclohexane [50–52]. Hydrogenolysis is utilised to recover phenolic monomers and oligomers [47]. While lignin oil is recovered through autohydrolysis [49], reductive catalytic fractionation [53], and/or solvolysis methods with the potential to produce high-quality lignin oil that can be blended with methanol for maritime fuel [48].

HL's studies use the TEA to identify and address process bottlenecks to lower the MSP. However, like biorefinery studies, these applications remain at the laboratory scale [46,55,56]. HL applications (Table 2) include bioethanol production via gasification and fermentation [56], Superactive Carbon (SAC) created through carbonisation for wastewater treatment [46], and carbon dots through amino modification [55]. Coupling lignin valorisation with bioethanol production can lower the MSP, but technological improvements are needed to enhance yield and MSP competitiveness [56]. For SAC, lignin cost represented the major share of the operating cost (OPEX), affecting profitability [46]. The carbon dot study highlighted that using lignin reduces production costs. However, further market analysis is needed due to the lack of a current market [55].

Despite a supply of KL, only three studies in the past two years used KL. The applications are hydrogen production through depolymerization [57], activated carbon (AC) using chemical activation [58], and bio-oil for HAVCs [59], as shown in Table 2. These laboratory-scale processes showed economic potential if scaled up. Valorising lignin for HAVCs is more profitable than burning it for electricity; however, it requires a larger investment in technology to purify the HAVCs [59]. For AC, the process using KL is shown to be competitive, but the initial KL price and the yield are key factors influencing market competitiveness [58]. Hydrogen production from KL is less viable compared to the alternative analysed methods due to lower yields and higher costs [57]. Other promising KL applications evaluated at higher TRLs had their TEAs published before January 2022, thereby placing them outside the scope of this study.

OL's studies shown in Table 2 mostly follow a biorefinery concept by valorising forestry residues into carbon materials such as AC for energy devices [60], carbon fibres (CF) for automotive applications [61], and chemical applications such as lignin monomers, oligomers [62], and aromatics [54]. AC and CF processes achieved a competitive MSP; however, AC price could be lowered if other biorefinery products are highly priced [60]. Meanwhile, CF production is more cost-effective than polyacrylonitrile (PAN), with potential cost reductions through lower lignin prices and higher plant capacity [61]. The chemical platform biorefinery is profitable with a lignin-first approach and could increase profitability by being integrated into pulp mills or sugar industries to reduce raw material

**Table 2**

**Overview of recently published TEAs that valorise lignin.**

| Technical Lignin | Technology/process used for lignin | Lignin end application | Scope TEA | Analysed indicators | Ref |
|---|---|---|---|---|---|
| Other lignin | Autohydrolysis | Lignin oil | Process optimisation | CAPEX, OPEX, sensitivity analysis, IRR | [49] |
| Other lignin | Base-catalysed deconstruction (BCD), fermentation, and hydrogenation | Adipic acid (ADA), electricity | Process feasibility, multiple scenario analysis | MSP, CAPEX, OPEX, revenue, sensitivity analysis, discount rate | [50] |
| Other lignin | Co-solvent enhanced lignocellulosic fractionation (CELF) & athermic oxygen removal | Cycloalkanes | Process feasibility, process optimisation | CAPEX, OPEX, DCF, MSP, sensitivity analysis, IRR, uncertainty analysis | [45] |
| Other lignin | Hydrogenolysis | Phenolic monomers and oligomers | Process feasibility | Revenue | [47] |
| Other lignin | Lignin conditioning (NaOH as catalyst), fermentation & hydrogenation | Adipic acid (ADA) | Process feasibility, multiple scenario analysis | MSP, CAPEX, OPEX, sensitivity and uncertainty analysis | [51] |
| Other lignin | Lignin upgrade (not explained) | Adipic acid (ADA) | Process feasibility, multiple scenario analysis | MSP, CAPEX, OPEX, DCFROR, sensitivity analysis, uncertainty analysis | [52] |
| Other lignin | Reductive catalytic fractionation (RCF) | Refined lignin oil (RLO) | Process feasibility, process optimisation | CAPEX, OPEX, MSP | [53] |
| Other lignin | Solvolysis | Crude lignin oil (CLO) | Process feasibility | MSP, CAPEX, OPEX, sensitivity analysis, | [48] |
| HL | Gasification-syngas & fermentation | Bioethanol | Process feasibility, process optimisation | CAPEX, OPEX, cash flow, discount rate, NPV, sensitivity analysis, MSP | [56] |
| HL, prehydrolised lignin (PHL), KL, OL | Hydrothermal method as pretreatment, followed by amino modification | Carbon dots | Process feasibility, process optimisation | MSP, CAPEX, OPEX | [55] |
| HL | Carbonisation | Superactive carbon (SAC) | Process feasibility | CAPEX, OPEX, MSP, NPV, IRR, payback period, sensitivity analysis | [46] |
| KL | Catalytic and thermal fast pyrolysis | HAVCs & electric energy | Process feasibility, multiple scenario analysis | ROI, NPV, OPEX, CAPEX, revenue, MSP, break-even point, payback period | [58] |
| KL | Chemical activation with KOH | Activated carbon | Process feasibility | MSP, IRR, revenue | [59] |
| KL | KL depolymerization | Hydrogen | Process feasibility | CAPEX, OPEX | [57] |
| OL | 2-step activation: Steam and carbon dioxide activation | Activated carbon (AC) | Biorefinery process feasibility | MSP, CAPEX, OPEX | [60] |
| OL | Base-catalysed depolymerization | Monomers and oligomers | Process feasibility | CAPEX, OPEX, revenue, sensitivity analysis, NPV | [62] |
| OL | Hydrogenation | Chemical platforms (aromatics) | Process feasibility, multiple scenario analysis and process optimisation | CAPEX, OPEX, ROI, IRR, Payback time, | [54] |
| OL-KL | Thermo-mechanochemistry | Carbon fibres | Process feasibility | MSP | [61] |
| LS | Copolymerization of LS & acrylic acid | Lignin-hydrogel | Process feasibility | MSP, CAPEX, OPEX, | [64] |
| LS | Catalytic hydrogenolysis (nickel hydrotalcite as catalyst) | Octane booster (acetophenone) | Process feasibility | Fixed capital investment, cumulative cash flow (CCF), CAPEX, OPEX, payback time, NPV, IRR, ROI, sensitive analysis | [63] |

costs [54]. In contrast, monomers and oligomers production was unprofitable at the analysed capacity, emphasising the need to scale up for economic viability [62].

Only two studies were identified using LS for the scope of this review: octane booster through catalytic hydrogenolysis [63], and hydrogels from LS and acrylic acid copolymerization [64]. Both applications have a favourable financial outlook with potential profitability improvements by enhancing the capacity for octane booster and reducing lignin costs for the hydrogels.

All the reviewed TEAs focus mainly on process optimisation by assessing the technical performance and economic feasibility of the lignin applications through the indicators shown in Table 2. This focus enables the determination of a competitive MSP and identifies the bottlenecks in the process, helping to develop new strategies to enhance the competitiveness of these lignin applications in the market. Additionally, several studies have combined life cycle assessment (LCA) with TEA to measure environmental sustainability. These studies demonstrate that lignin valorisation can be profitable while reducing carbon emissions [48,53,54]. Nonetheless, some cases were not economically viable despite having lower carbon emissions [56,62]. Economic viability and environmental benefits do not always align; valorising lignin instead of burning it could enhance profitability but might also increase emissions. While burning lignin might be more profitable and emit less than coal or natural gas, using renewable energies could further cut emissions, improving the benefits of lignin valorisation [50–52].

## Lignin outlook in the green transition

COP 28 proclaimed the beginning of the end of the fossil fuel era, aiming to cut down on the use of fossil fuels to reduce carbon emissions by 43 % [65]. Bio-based products tend to emit, on average, 45 % less than their fossil fuel counterparts [66], and some lignin applications showed an emission reduction which can support reaching COP 28's goal [48,53,54,56,62]. Funding these economically feasible applications is key. Therefore, initiatives, such as Bio-based Industries Joint Undertaking (BCE-JU), are financing circular bio-based applications in Europe. These initiatives aim to develop and integrate innovations such as lignin applications (e.g., LIGNICOAT) into existing value chains, contributing to the goals of decarbonisation and circularity [67].

In alignment with these goals, Finland is leading by example with its Bioeconomy Strategy, which aims to double the bioeconomy's share of the national economy by 2035. Finland's forest sector is a key player in this strategy, focusing on expanding the added-value portfolio of lignin. The Forest Bioeconomy Science Panel's recent report visualises valorising 20 %–40 % of Finland's available KL into different applications, potentially adding €670 to €1500 millions in total value [68]. This would significantly boost the sector's economic contribution while meeting biodiversity and climate targets. These scenarios highlight KL's potential in Finland as an example to other countries to support the global green transition.

## Summary

Lignin has the potential to reduce dependency on fossil fuels in several applications. As the green transition advances, there will be a higher demand for KL to be valorised to provide alternatives to existing products. To meet this demand, collaboration among researchers, governments, policymakers, and companies will require additional investments. The reviewed TEAs highlight that lignin pricing and increased plant capacities are crucial factors in determining the feasibility and market competitiveness of new lignin processes and products.

Expanding the product portfolio and increasing profit margins will drive future efforts and research in lignin use. The pulp and paper industry is undergoing significant changes because of the green transition, including mill closures. As seen in initiatives from Finland, there is an urgent need to diversify and pursue new value creation pathways.

TEAs are essential for assessing the economic viability of lignin-based processes and guiding strategic decisions for market integration. These assessments help stakeholders navigate the challenges of lignin utilisation and unlock its full potential to generate sustainable innovations and economic growth.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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