Why Can We Make Anything from Lignin Except Money? Towards a Broader Economic Perspective in Lignin Research

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Abstract

Purpose of Review As a major component of wood, lignin is regarded as a promising, bio-based compound which could strongly influence the forest-based circular bioeconomy. Much research has been conducted on the material use of lignin, but the lignin commercialization process is still under development; few commercial production facilities and larger-scale applications are available. Therefore, we present a review of recent research papers on the economic perspectives on lignin.

Recent Findings Research has been conducted on lignin application areas such as lignin-derived polymeric materials, polymer and composite systems, applications for micro-sized and nano-sized lignin, energy storage, and renewable chemicals. On the whole, the life cycle assessment results indicate that lignin-based innovations can be environmentally beneficial. Techno-economic studies identified the lignin feedstock cost and the achievable product price as the most sensitive factors. Recently, researchers pointed out information asymmetries between different stakeholder groups concerning lignin-containing products.

Summary Although most of the relevant papers presented a technical perspective of lignin, a smaller set of general economic statements about lignin appear in these papers. These statements refer to lignin underutilization, limited markets, resource abundancy, and barriers to utilization. The literature on technical lignin with an economic perspective can be divided into two different streams: several techno-economic papers and fewer socio-economic papers. The former placed a primary focus on production processes from a profit maximization perspective, but attempts were also made in the latter to explain the socio-technical innovation system. To date, lignin researchers have focused mainly on internal (direct) factors but have not yet sufficiently considered external (indirect) factors.

Keywords Lignin sustainability · Lignin techno-economic · Lignin market · Lignin biorefinery · Lignin innovation · Cross-sectoral collaboration

Introduction

Forest-Based Biorefinery Research and the Case of Lignin

Lignocellulose is considered to be the most abundant terrestrial plant material [e.g., 1]. In research papers dedicated to biorefinery development, this material amounts to approximately 60% of all feedstock mentioned [2]. Forest-based or wood biorefineries have the potential to provide a readily available feedstock, allowing for a relatively broad product portfolio [3]. These biorefineries reduce competition for food and feed as compared with most starch-, sugar-, and oil-based feedstocks and could contribute to the replacement of fossil-based resources to a certain extent [3].

In the context of the forest-based circular bioeconomy, lignin is considered as a key to commercial success, potentially

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representing between 24 and 47% of the current returns from pulp production [3]. Wood-pulping processes are usually developed and optimized for the generation of high-quality cellulose (cellulose makes up 40–50% of wood), whereby current biorefinery operations are not geared towards the isolation and valorization of other major wood constituents such as hemicelluloses (25–35% of wood) and lignin (18–35% of wood) [4–6]. Hellsmark and Söderholm [7] suggested that biorefineries could serve as a platform to revitalize the mature pulp and paper industry [7], which is the major producer of technical lignin, such as Kraft lignin and lignosulfonates [1•, 8]. Pulping facilities around the world produce an estimated 40–50 million tons per year of this technical lignin [e.g., 8–11], which is currently mainly burnt on-site (about 95–98%) to recover the process chemicals and obtain energy [e.g., 4, 9, 12]. However, a surplus of lignin is produced, especially due to improvements in the energy efficiency of pulp mills [e.g., 13, 14]. This surplus could enable value-added products to be produced from part of the generated technical lignin without affecting the required energy supply [13, 15, 16••]. Today, only a small amount (i.e., approximately 2%) of the available lignin is isolated from spent pulping liquors and used commercially [e.g., 12, 17]. Despite the large quantities of technical lignin available from the dominant Kraft process, lignosulphonates are currently more strongly established on the market than lignin from black liquor [e.g., 16••].

Lignin is regarded as a promising bio-based compound and is expected to play an important role in biorefinery design [3]. For example, it is generally considered as an underutilized side-stream and the major existing bio-based aromatic resource [18]. It has the potential to yield a wide variety of products, which are currently under investigation [12, 18, 19]. Much research has been undertaken to identify the higher-value uses of lignin; nevertheless, the commercialization of lignin is still under development, with few commercial production facilities and larger-scale applications available [16••]. Accordingly, a common saying among representatives of the pulp and paper industries is “one can make anything from lignin except money” [18.; p. 716].

Therefore, we conducted a comprehensive review of lignin research and specifically identified papers in which an economic perspective was taken. The conclusions drawn from the synopsis of the reviewed papers help to contribute to a better overall understanding of lignin-related innovation systems. By identifying research gaps that still need to be filled, we describe some reasons why the commercialization of lignin still faces significant challenges and suggest ways these challenges can be met.

General Approach and Structure of the Paper

To achieve these research objectives, we applied a systematic approach. A detailed description of the approach taken,

including the search terms and (number of) papers identified, can be found in the supplementary material (ESM 1).

Therewith, we identified relevant research papers and classified these within the following three topical domains in lignin research. The first domain contained papers (scientific articles and reviews) which have a focus on natural-science and technology-related aspects. These papers also contained, for instance, information on conceivable applications of lignin, general assumptions about its market potential, and market information and data from different (non-scientific) sources, such as commercial market reports and trade databases. The second domain encompassed papers in which a focus was placed on sustainability assessments (mainly regarding the environmental performance) and/or techno-economic assessments (TEAs) of lignin. These studies were mostly based on certain process technologies and specific assumptions. The third domain included a smaller number of socio-economic papers in which drivers and barriers that are important from a more holistic perspective were addressed, e.g., related to external factors necessary for lignin-based products to be successful on the market.

This paper is structured as follows:

- (1) In the section entitled “[Current Research on Lignin: the Research Output, Considered Applications, and Market-Related Aspects](#),” we provide a short overview of the development of lignin research in recent years. Ten general and frequently occurring statements about the economic aspects of lignin were collected from papers and books (which were not based on market-based approaches) using a snowballing approach (see file ESM 1). This perspective on the use of lignin was complemented by highlighting current review papers that placed a primary focus on the possible future applications of lignin and certain papers that summarized market information from different non-scientific sources (these papers were selected with a systematic approach, see file ESM 1). Two figures are included in this chapter: Fig. 1 illustrates the increase in lignin research that has occurred in recent decades, and Fig. 2 displays the occurrence of selected, application-related search terms in the lignin literature.
- (2) Next, in the section “[Sustainability and Techno-Economics in Lignin Research](#),” we review the use of wood-based lignin for non-fuel applications from the perspectives of sustainability (mostly environmental impact assessments) and techno-economic assessments (TEAs). A summary of the approaches (nine sustainability assessments and ten TEAs), utilization pathways, and major findings is provided, including an overview table on the TEA papers.
- (3) Then, in the section “[Socio-Economic Assessments in Lignin Research](#),” we focus on lignin commercialization

from the product, consumer, and market perspectives. Relevant papers (a core of seven market-related papers) were identified (see file ESM 1). These papers were reviewed in detail to investigate the status quo in this branch of the scientific literature, to draw lessons from the major findings of these papers, and to identify research gaps. In this section, we provide a description of the investigated papers, an overview table, and a figure illustrating the socio-technical system, which includes the identified drivers of and barriers to lignin innovation diffusion.

- (4) Finally, in the section “**Conclusions and Discussion**,” we describe how an investigation of the identified research gaps may allow researchers to make a positive contribution towards a broader understanding of lignin commercialization on a larger scale. In addition, we discuss the findings in the context of the innovation literature, and, in particular, in the context of wood-based biorefineries and the forest-based circular bioeconomy.

Current Research on Lignin: The Research Output, Considered Applications, and Market-Related Aspects

The amount of research on the topic of lignin has strongly increased in recent decades, as illustrated in Fig. 1. Abejón et al. [20] carried out a bibliometric analysis on research trends concerning lignin valorization; for this purpose, they analyzed 353 papers published from 2000 to 2016 (using the Scopus database and searching for the terms “lignin” and “valorization” in the abstracts, titles, and keywords). They observed an exponential annual increase in the number of papers published on this topic (from six papers altogether before 2008 to 108 papers published in 2016). This positive trend has continued since then, with 322 papers published in 2019 using the same

search string. The numbers of scientific lignin articles published, in general, and of lignin reviews (highest numbers in 2019: 1538 articles and 99 reviews) have also strongly increased over the last few years (Fig. 1). These papers mainly have addressed technology issues. The reviews provide concise summaries of various sub-topics, such as overviews of the most common sorts of technical lignin and their properties and/or their potential applications [e.g., 21–25]. Diverse valorization approaches are addressed in these reviews, which deal with the separation, modification (e.g., depolymerization), and/or upgrading of lignin [e.g., 1•, 4, 26–30], such as microbial lignin valorization [e.g., 31–35].

Most of the scientific literature on lignin presents research approaches in the fields of the natural sciences and technology, and little attention has been paid to lignin-based products and market aspects [16•, 36•]. Nonetheless, it is noticeable that—probably due to the fact that much of this research could eventually lead to an economically advantageous use of lignin—general statements about the economic relevance of lignin have often been made, for example, about its future potential. A rather small set of general statements on lignin applications and market aspects seems to have been made repeatedly, although references are often lacking for these stated assumptions. In the following section, the most commonly collected statements are summarized according to their meanings. They are listed in descending order by the frequency of mention (for detailed information on the frequencies of the statements and the reference list, see the supplementary material ESM 1):

- Lignin is a very abundant resource.
- Currently, the market for lignin is limited (heat and power, vanillin, lignosulphonates, niche markets).
- There is a barrier to lignin utilization, and lignin valorization is a challenge for several reasons.
- Further research and development/new processes could eventually enable the scalable production of lignin-based products: further research and development are needed.

Fig. 1 Number of papers about lignin published between 1990 and 2019 (Scopus database: lignin or lingnosul* in the title of a scientific article or review)

APPLICATION-RELATED SEARCH TERMS, ABSOLUTE FREQUENCY OF OCCURRENCE (NUMBER OF PAPERS), AND RELATIVE FREQUENCY OF OCCURRENCE (WITH REFERENCE TO THE LIGNIN DATASET, N = 16,700)
 TITLE (lignin OR lignosul*) AND TITLE-ABS-KEY (application-related search term) AND (LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (PUBYEAR , 2020))

Fig. 2 Search hits with selected, application-related search terms that occur in the titles, abstracts, or keywords of papers from a body of literature on the topic of lignin (Scopus database: lignin or lingnosul* in the title of scientific articles published up until 2019)

- Lignin is underutilized.
- Lignin plays a major role in biorefinery conception.
- The use of lignin for certain applications could reduce costs.
- Lignin is a sustainable, environmentally friendly material.
- Lignin is a promising material and has the potential to serve as an alternative to other materials.
- The amount of available lignin will increase.

Applications Considered in Research

A clear focus on the technology- and natural-science-related aspects of lignin was observed in the scientific literature. This has also been due to challenges associated with characteristics inherent to the (technical) lignin [e.g., 18, 23, 26]. These challenges, in turn, have driven research efforts to develop technology for biomass pretreatment and lignin separation to achieve an adequate quality, advanced chemical analyses to more precisely characterize lignin, and conversion approaches to create more valuable products [23].

Several reviews in recent years have addressed certain application areas [e.g., 8, 21, 37–39]. These areas include lignin-derived polymeric materials [40–42], lignin in polymer and composite systems [8], applications for microsize and nanosize lignin [25, 43], lignin in storage and energy applications [44], lignin in food and/or pharmaceutical industries [24, 45], and lignin for renewable chemicals [28]. Li and

Takkellapati [1•] reviewed technical lignin sources, identifying valorization approaches and applications and focusing on their practical implementation. Figure 2 shows the relative frequency of occurrence of selected, application-related search terms in the literature on lignin (search conducted in titles, abstracts, and keywords; for more details see file ESM 1).

Market-Related Aspects and Data Outlined in Research Papers

With regard to the economic aspects related to these applications, little information is available in most of these papers. However, certain sources such as trade databases, market reports, and patents provide relevant information about lignin and its potential application fields. Information on markets (e.g., prices of products that are potentially replaced by lignin) have been collected and considered by several authors, either to review these aspects or to make valid assumptions as a basis for, e.g., techno-economic assessments.

Four review papers were identified that placed a strong focus on lignin markets and applications. Dessbesell et al. [16••] examined scientific peer-reviewed publications, supply and market publications, as well as patents on lignin. They provided detailed information on the global lignin market and supply, placing a special focus on phenols and polyols from Kraft lignin. The importance of these two application fields in the short- to mid-term was emphasized. The authors also recommended that only the Kraft lignin surplus, which is not

needed as an energy source on-site, should be considered for chemical and material applications [16••]. Bajwa et al. [36•] described lignin sources and types, market volumes, and prices, as well as current and emerging applications, including market prices. They recommended the use of tools such as techno-economic assessments (TEAs) and life cycle assessments (LCAs) to identify the benefits and challenges of valorization pathways [36•]. Hodášová et al. [22] listed price ranges for several lignin types and for potentially replaced products. They focused on three groups of applications: (a) the use of depolymerized, aromatic compounds from lignin, (b) the use of lignin as a macromolecule, and (c) the use of carbon material from lignin. They concluded that lignin as a macromolecule is more highly developed than the applications of the other two groups, despite their higher market value. In particular, aromatic compounds from lignin were considered to have the greatest potential [22]. Graichen et al. [46] stated that lignin and other bio-based products could achieve market success, and they described some challenges that would need to be overcome to achieve this: (1) Capital and funding were identified as critical issues; (2) there is competition for biomass, and it needs to be available in sufficient quantity and quality; (3) the bioeconomy requires interdisciplinary and cross-sectoral communication and cooperation (new value chains); (4) innovations are often associated with high infrastructure costs; and (5) regulatory measures are strong drivers, but also unpredictable and often not fully understood by relevant stakeholders [46].

Brief overviews of market-related aspects were found in several papers. Lucid plots that illustrate market prices versus market volumes of potential applications were provided by Gabriel et al. [47] and, most recently, by Dessbesell et al. [16••]. Prices and/or price ranges and production volumes for different lignin types were collected from different sources and were reported in several papers [e.g., 47, 48, 49•]. Prices and/or volumes of a range of potentially substituted products were also reported in several sources [e.g., 26, 47, 48, 50]. Companies and plants that already produce lignin and/or lignin-based products were mentioned in several papers. Detailed descriptions of these are provided in Dessbesell et al. [16••], Bajwa et al. [36•], and Li et al. [33]. The latter published overview tables on the key players on the lignin market, including the industrial lignin applications. Lignin patents were reviewed by Dessbesell et al. [16••], and lignin patents with applications in food and pharmaceutical industries were reviewed by Gil-Chávez et al. [24].

Sustainability and Techno-Economics in Lignin Research

The lack of available information on sustainability aspects in lignin research has been mentioned in several papers [e.g.,

36•, 44]. However, a small body of literature includes information on life cycle assessments (LCAs) and techno-economic assessments (TEAs) related to lignin, some of which were reviewed by Bajwa et al. [36•]. In the following section, we review selected LCA and TEA papers that were published in the last 5 years (2015–2019) and address wood-based lignin for non-fuel applications. Several assessments of uses for lignin from agricultural residues and/or uses of lignin for fuel applications are available [e.g., 49•, 50–58], but this topic was considered beyond the scope of this paper.

Environmental Impact Assessments in Lignin Research

The intended use of lignin for various applications is based on the premise that this undertaking would contribute to increased sustainability (in particular, the environmental performance of lignin-based products as compared with their current, often fossil-based counterparts). However, the broad spectrum of available ways to gain, valorize, and use lignin that are currently discussed in the scientific literature indicate that it is necessary to prove whether a considered option actually increases overall sustainability [36•]. For this reason, some authors have recommended supporting the product development with accompanying sustainability assessments, already starting during early research stages [59].

Several papers that described the use of such approaches with lignin were published recently. Bajwa et al. [36•] reviewed several LCA papers related to lignin and concluded that using tools such as LCA supports decision-making and allows users to select the most appropriate, lignin-based product design for future commercialization [36•]. A focus was placed on sustainability aspects of wood-based lignin for material or chemical applications in papers published on the following topics:

- An LCA of Organosolv lignin for tertbutyl catechol, and a comparison with the fossil-based counterpart [60]
- The impact of integrating a lignin extraction with LignoBoost in a softwood Kraft pulp mill for phenol-formaldehyde (PF) adhesives [61]
- An LCA of a medium-density fiberboard (MDF) with a hybrid-modified ammonium lignosulfonate as binder, as compared with conventional MDF [62]
- The identification of environmental hotspots and sustainability levers of Kraft lignin valorization pathways for PF resins [59]
- The identification of an optimal process for using alkali lignin from Kraft pulping for vanillin production, using LCA and green design metrics [63]
- Environmental performance and “burdens shifting” resulting from pulp and bioethanol processes when a lignin fraction is removed; Kraft LignoBoost lignin for non-

specified high value applications between 1000 and 2000 €/t [64]

- The environmental performance of wood-based fiber laminates with hardwood Organosolv-lignin-based phenolic resins [65]
- A meta-LCA for screening purposes to analyze lignin-based and recycled carbon fibers in composites [66]
- A multi-regional input-output (MRIO)-based approach for analyzing the possible substitution impacts (environmental and socio-economic indicators) of using a part of the surplus lignin from the pulping industry in the chemicals sector, therewith substituting fossil-based resources [67]

On the whole, the results of these studies indicate that lignin-based innovations have the potential to be environmentally friendlier than current non-renewable alternatives regarding several impact categories, thus giving a positive outlook that lignin utilization could contribute to improved sustainability. This utilization refers primarily to environmental aspects, however, so significant research gaps may exist in terms of social aspects. The sustainability of lignin innovations should be assessed on a case-to-case basis, as the processes, approaches, and assumptions (e.g., the system boundaries and the allocation approaches used) are highly specific for each case and, therefore, can influence the outcome of such studies [e.g., 68, 69]. The sustainability-focused approaches also have the potential to reveal environmental hot-spots and to support decision-making for sustainable processes and products throughout the innovation process [e.g., 59].

Techno-Economic Assessments in Lignin Research

In Table 1, the TEAs conducted over the last 5 years (2015–2019) are summarized. These studies address the production and/or processing of forest-based lignin for non-energy applications: The feedstock (input for the lignin product), major processes considered, intended product, and/or application (including potentially substituted material), investigated country, and planned capacity of the biorefinery, as well as some major findings and conclusions are presented. Under the assumed conditions and scenarios, some approaches were found to be potentially economically feasible, while others were not considered as profitable at present (i.e., those applied to substitute phenol, for which the considered market price is too low). There are significant uncertainties regarding several assumptions made in these approaches, and varying these assumptions can yield different results. Therefore, the most commonly mentioned sensitive factors will be briefly described.

Almost every paper mentioned a major sensitive factor related to the cost of the lignin feedstock [10, 14, 48, 70, 72–75], which could be crucial in determining the process feasibility. The second-most frequently mentioned sensitive

factor concerned the market prices that can be obtained for the final product [14, 72–75]. Plant capacity [10, 70, 73] and, in particular, the increase in capacity represented factors that critically affected the profitability of a biorefinery. Other sensitive factors that were indicated included the costs for diverse input materials other than the lignin [14, 48, 75] and technology- and product-quality-related factors [e.g., 10, 71]. Given the high degree of uncertainty and sensitivity associated with lignin costs and prices, lignin products, and the market demand for these, the techno-economic assessments could be improved if investigations of the market environment are carried out to reduce such uncertainties.

Socio-Economic Assessments in Lignin Research

While several approaches exist to assess the environmental performance and techno-economics of lignin, few studies have been carried out to explore the possibilities associated with bringing value-added lignin products onto the market [9]. Other than the existing, rather specific papers on TEA and LCA, few papers present research approaches to investigate the market for or the sustainability of lignin in the broader sense of innovation systems. In the following section, these few papers are discussed in more detail and summarized in Table 2. Identified drivers and barriers that were considered to be relevant for the innovation diffusion of lignin and lignin-containing products are summarized in Fig. 3.

Hall et al. [76] described the so-called “Eroom” effect in combination with sustainable innovation, whereby lignin utilization (for vanillin and carbon fibers) represented one case study out of two. The phenomenon of improved price-performance (Moore’s law, Carlson curve) tends to be counteracted by the downstream costs for new technologies (e.g., for regulatory approval, labeling, and trade policies), which present particular challenges for public (e.g., universities) or smaller institutions. The authors concluded that labeling was a major issue in the case of Canadian lignin-based vanillin, and the use of carbon fibers was subject to major challenges regarding trade restriction policies and regulatory approval in the USA [76]. Lettner et al. [77] investigated factors that influence the market diffusion of bio-based plastics, whereby the feedstock lignin represented one case study out of four in the comparative case study approach. They concluded that the most viable scenario for increasing the substitution potential involves improving the properties and promoting technological innovation, thus contributing positively to the objective of increasing sales volume and reducing product price [77]. Lettner et al. [78••] analyzed the knowledge gaps (information asymmetries) between different stakeholder groups concerning Kraft-lignin based phenol-formaldehyde (PF) resins for wood-based panels and lignin-based

Table 1 Overview of recent (2015–2019) techno-economic assessments related to the production and/or processing of forest-based lignin for non-energy applications: feedstock (input for the lignin product), major processes considered, intended product, and/or application (including potentially substituted material), investigated country and planned capacity of the biorefinery, as well as some major findings and conclusions

Raw material/input	Process	Product	Applications	Substituted product	Capacity	Country	Main findings/Conclusions	Paper
Kraft lignin, liginosulfonate	Aerosol/atomization method	Lignin microparticles and nanoparticles (LMNPs)	Several; e.g., emulsion stabilizers, UV protection	Particles (synthetic or mineral)	150 t/day LMNPs	US	Manufacturing costs estimated between 870 and 1170 USD/t; minimum selling prices varied from 1240 and 1560 USD/t	[48]
LignoBoost Lignin	Concentrated solution of lignin in THF and ethanol introduced into water (self-assembly)	Colloidal lignin particles (CLP dry powder)	Several; e.g., phenol–formaldehyde (PF) resins, foams	PE, PP, PET, phenol	50 kt per year of dry colloidal lignin	(probably Finland)	Total investment cost (integrated plant): 36 M€; annual operating cost: 46 M€ (project lifetime: 20 years); payback period with a CLP selling price of 1.10 € kg ⁻¹ : roughly 5 years; in the current scenario, CLPs can compete with PE, PP and PET, but slightly not with phenol and PET, but slightly not with phenol	[70]
Wood chips	Solvent recovery strategies and their implement. for lignin value prior to pulping with water precipitation	Organosolv-like lignin	(Not indicated)	(Not indicated)	~ 80,000 metric t/year precipitated lignin	(probably US)	Annual costs prohibitive for lignin commercialization due to required lignin selling price of a few times its fuel value; new separation techniques or a higher lignin selling price required to be economical	[71]
Softwood Kraft lignin + LignoForce	Kraft lignin depolymerization (DKL) and oxypropylation (Oxy-DKL) processes	DKL (powder) and Oxy-DKL (viscous liquid)	Polyurethane foams and phenolic resins	Phenols and polyols	3 kt Kraft lignin per year (2.7–5.6 t/year final product)	Canada	Great variation in cost drivers, but DKL phenol and Oxy-DKL polyol attractive options to compete in the polyols market (MSP: 1440 and 1623 USD/t, respectively); DKL not feasible when replacing phenol due to the current low market price of phenol	[72]
Kraft lignin	Proprietary low-temperature/low-pressure lignin depolymerization process	Depolymerized Kraft lignin	PF resins in engineered wood products (e.g., plywood)	Phenols and polyols	Several scenarios: 10 kt/year, 40 kt/year, 80 kt/year, 120 kt/year	Canada	Tot. variable manu. Cost: ~1081–1101 USD/t, tot. Fixed manu. Cost: ~63–154 USD/t; all scenarios feasible, but investment more attractive with larger capacities; 120,000 t/year of KL with 85% EG recovery rate: most attractive NPV (USD 148.4 M) and PBP (2.7 years)	[14]
Softwood Kraft lignin + LignoForce	Pyrolysis	Pyrolysis dry oil	(Phenolic) chemicals, e.g., for resins	Petro-chemical phenolics	50 t/d dry basis	Canada	Selling price cannot compete with the price of fossil-based chemicals (reasons: high feedstock cost, oil yield, plant capacity); lignin costing max. 200 \$/t should be found; converting lignin to phenol for resin prod. is a costly-process compared with using lignin itself as phenolic-substrate	[10]
Indulin AT Kraft lignin, Protobind 1000 soda lignin	(Non-catalytic) lignin pyrolysis, direct hydrodeoxygenation (HDO), and hydrothermal upgrading (HyThUp)	Mixed oxygenated aromatic monomers (MOAMON), light organics, heavy organics, char	Bio-based chemicals	Petro-chemical aromatics	200 kt/year lignin input	Netherlands	Further development and commercialization of HDO recommended: highest operating costs, but highest ROI (12%), shortest PBP (5 years) due to high yields of heavy organics (32%) and MOAMON (24%),	[73]

Table 1 (continued)

Raw material/input	Process	Product	Applications	Substituted product	Capacity	Country	Main findings/Conclusions	Paper
Olive tree pruning	Organosolv ethanol, alkaline depolymerization (NaOH), catechol separation (filtration, distillations)	Catechol	(Not indicated)	(Not indicated)	2544 kg/d of feedstock	Spain	positive NPV based on assumed prices; other two processes: neg. NPV Total capital investment of the plant ~4.9 M\$ [74] based on assumed plant capacity; estimated catechol price: 1100 \$/t, valorization ratio: 3.02; results indicate interesting position of the product in the market	[74]
Oil palm empty fruit bunches (OPEFB)	Three diff. pretreatments: sequential acid-alkaline (AAP), steam explosion followed by alkaline delignification (SEAP), steam explosion (SEP)	Ethanol, xylitol and lignin	(Not indicated)	(Not indicated)	200,000 tons dry OPEFB/y; leading to lignin prod. of 36,745 t/year (AAP), or 16,500 t/year (SEAP)	Brazil	Largest yearly profit: SEAP, followed by AAP; profit attributed to production of xylitol and lignin; SEP: negative yearly profit; OPEFB could be feasible if all fractions obtained in pretreatment stages are valorized; 21,500 t/year ethanol, 17,550 t/year xylitol and 36,745 t/year lignin produced	[11]
Beech wood	Organosolv (ethanol-water) pretreatment, enzymatic hydrolysis, alcoholic fermentation, dehydration, biogas generation and upgrading	Polymer-grade ethylene (main product), Organosolv lignin, methane, hydrolysis lignin	Chemicals (polymer-grade ethylene, Organosolv lignin), fuels (methane, hydrolysis lignin)	Petro-chemicals	400,000 dry tons/year beech wood; leading to 58,520 t DM/a Organosolv lignin	Germany	Concept not profitable enough; under certain conditions (e.g., slightly higher ethylene selling price), cost-effective operation within chemical industry possible; 61,600 t/a ethylene, 58,520 t DM/a Organosolv lignin, 38,400 t/a biomethane and 90,800 t DM/a hydrolysis lignin produced	[75]

Table 2 Overview of papers that focus on socio-economic aspects towards the innovation diffusion of lignin-containing products: aim of paper, methodological approach, scope, considered lignin feedstock, intended lignin application, main findings, and conclusions

Aim	Approach	Scope	Feedstock	Lignin application	Main findings/Conclusions	Paper
Describe the “Eroom” effect in combination with sustainable innovation; lignin is one case study out of two	Discussion of a paradox in the context of sustainable innovation: phenomenon of improved price-performance (Moore’s law) in relation to increase of downstream costs for new technologies (“Eroom” effect)	Stronger focus on USA, but discussion not limited to region	(Not specified)	Vanillin and carbon fibers	Drivers and barriers within an innovation system exist that are not directly associated with the lignin (such as labeling, trade policies, and regulatory approval)	[76]
Investigate factors that influence the market diffusion (of increasing the sales volume and decreasing the product price); lignin is one case study out of four	Comparative case study approach; normative scenario analysis, effects analysis; cross impact analysis; online survey	Experts (not limited to region) from bioplastics research and advocacy groups	(Not specified)	Bio-based plastics	Technology foresight; increase of the substitution potential by enhancing the properties and promoting technological innovations, accompanied by marketing activities recommended	[77]
Identify diffusion gaps (based on lignin attributes); Identify knowledge gaps between different stakeholder groups	Comparative Importance Performance Analysis (online survey); open question regarding barriers and incentives	Stakeholders groups along the value chain (from European companies and from academia)	Kraft-lignin	PF resins for wood-based panels; PU resins for PU foams	Information asymmetries between stakeholder groups along the value chain exist; need for cross-sectoral collaboration, and strong communication/cooperation	[78•]
Investigate innovation barriers, incentives, and valuation gaps (between academia and industry)	Adapted three-phase Delphi method (multistage expert interview approach); identification of factors, separation into knock-out and variable factors, ranking of the importance of variable factors, identification of barriers and incentives	Experts from the wood-based panel industry, chemical industry), pulp industry, and research organizations	Modified Kraft lignin	Resin substitute in the wood-based panel industry	Relevance of socio-economic issues (besides technical performance), that require cross-sectoral collaboration; information asymmetries	[79]
Identify barriers and incentives for the market diffusion	Two-stage Delphi approach; key-factors structured into a SWOT matrix; open question on barriers and incentives	Experts from relevant European and North American industries (pulp and paper, composite production and application), and research organizations	Kraft lignin and lignosulfonates	Composites and blends (with PLA, PP, and PE), lignin as thermoplastic component	Improved interactions between stakeholder groups, cross-sectoral networks, and the roles of end-consumers and policy are needed	[80]
Identify most relevant attributes, diffusion barriers, and opportunities	Two-phase market analysis-based approach: PAC vendor content analysis (assess relevant criteria), and buyer/user e-survey	Electric generating power plants with activated carbon injection systems in the USA	Lignin waste streams from pulp mills and biorefineries	Powdered activated carbon (PAC) for mercury sequestration of flue gas from electric generating power plants	Information asymmetries; drivers and barriers within an innovation system exist that are not directly associated with the lignin (e.g., existing vendor contracts, compliance with regulations)	[9]
Investigate the current market situation and trends	Survey via telephone: questions related to the following topics were asked: products (plasticizer and superplasticizer) currently used, products previously used, importance of the product price, and statistical data of company and respondent	Representatives from companies that produce ready-mixed concrete in Austria or Southern Germany (mainly managers of the testing laboratories, but also managing directors, plant managers, procurement and division managers)	Wood-based lignosulfonate	Substitute for synthetic polycarboxylate in concrete admixture systems	Besides technological performance, factors within an innovation system exist that are not directly associated with the lignin (e.g., mandatory industry standards); transaction costs	[81]

Fig. 3 Multi-level perspective towards transitions (adapted from [82] to the case of lignin) with drivers and barriers for the innovation diffusion of lignin-containing products (identified from papers in which research

approaches are followed in the broader sense of innovation systems or cross-sector collaborations [9, 76, 77, 78••, 79–81])

polyurethane (PU) resins for PU foams by conducting an importance-performance analysis (IPA). The authors recommended reducing information asymmetries by cross-sectoral collaboration, improved communication, and new cooperation among stakeholders along the whole value chain [78••]. Stern et al. [79] investigated innovation barriers, incentives, and valuation gaps (between academia and industry) of modified Kraft lignin in the wood-based panel industry (partial replacement of fossil-based resins) using a multistage expert interview approach. Taking a similar, two-stage Delphi approach, Schmelzenbart et al. [80] identified barriers and incentives for the market diffusion of composites and blends (with PLA, PP, and PE) that contained Kraft lignin and liginosulfonates as thermoplastic components. To overcome bottlenecks, the creation of new value chains, the improvement of stakeholder interaction, the need for cross-sectoral networks, and the consideration of the role of end consumers and policy were mentioned as important factors [80]. Cline and Smith [9] applied a multi-phase, market-analysis-based approach to provide an exploratory market perspective on lignin-based powdered activated carbon (PAC) that could be injected into electric generating power plant flue gas to sequester mercury by adsorption. Earlier, Stern and Schwarzbauer [81] had investigated the current market situation and trends for wood-based liginosulfonate, comparing it with synthetic polycarboxylate in

concrete admixture systems. They concluded that recent mandatory standards, weaker technological performance, and lower producer market power were responsible for a downward trend in the use of liginosulfonate-based plasticizers. With regard to switching costs, the authors found that price changes of around 14% encouraged the concrete industry to switch products [81].

The authors of seven papers that included results of socio-economic assessments identified drivers for and barriers to the innovation diffusion of lignin-based products. These were identified as not only being related to technical aspects but also to other aspects that are relevant in the socio-technical system [82, 83]. The drivers and barriers were collected, combined, and assigned to components of the socio-technical system [82] (Fig. 3). The multi-level perspective on transitions sometimes encourages the use of different definitions for the terms “system” and “regime”; in this paper, we use the term “system” as an umbrella term for both the tangible elements and the “underlying deep structures” [83]. The overview is not exhaustive but illustrates the drivers and barriers that have been identified thus far, contributing towards a broader system understanding. Table 2 summarizes the aims, approaches, and scopes of these papers, as well as the lignin feedstock and applications indicated. The main findings and conclusions, aside from the cost/price and technical requirements, are

highlighted. These are related to relevant factors that are not directly associated with the lignin (e.g., labeling, trade policies, regulatory approval, vendor contracts, and industry standards), information asymmetries between stakeholder groups along the value chain, transaction costs, and the strong need for cross-sectoral collaborations and networks.

Conclusions and Discussion

The vision of efficient forest-based biorefineries will not become reality until lignin has been successfully commercialized [84–88]. This successful commercialization will have a major impact on wood prices and, thus, promote the profitability of forest management [3]. However, the large-scale, effective commercialization of lignin has not yet taken place [e.g., 16••]. Despite the fact that researchers have invested a reasonable amount of efforts over the last 30 years in investigating technology-related issues, such as the extraction, characterization, and application of technical lignin, the application of lignin is still limited to energy production and some niche applications [e.g., 17, 18, 85, 89]. At the same time, scientific publications refer to lignin as abundant [e.g., 17, 18, 85, 89] and underutilized [e.g., 5, 18, 19, 85]. From an innovation theory perspective, this indicates that the raw material availability is pushing the respective innovations forward (availability push), while the technical aspects have been perceived thus far as the major barrier to valorization [e.g., 5, 17–19, 85, 90]. Accordingly, recent literature reviews have mostly placed a focus on specific application fields, with authors taking rather technological viewpoints [e.g., 1, 8, 24, 40, 41, 43, 44]. It may be argued that technology-related aspects, such as the proper characterization of technical lignin and an understanding of structure-property relationships, are needed before a valuation can be achieved. However, producible lignin qualities are highly variable, considering the different feedstocks, production processes, and modification and application options that are currently under investigation. Hence, it seems more efficient to consider technical aspects and valuation as iterative actions.

The literature addressing technical lignin from a sustainability or economic perspective can be divided into two different streams: TEA and LCA studies and socio-economic papers in which an innovation or market perspective is typically taken. While the TEAs and LCAs are generally based on data from technological research, and mainly cover production processes and their impacts, the latter refer to stakeholder interactions in research and development (R&D) processes or on the markets.

The TEAs frequently identified the cost of the lignin feedstock [10, 14, 48, 70, 72–75] and the achievable market price for the final product [14, 72–75] as the most sensitive input factors. The considerable cost of wood, as a major lignin

feedstock in lignocellulose biorefineries, is dependent on allocation procedures [e.g., 68, 69] and may be influenced by lignin utilization in terms of an increased wood-paying capacity if competition for the resource increases [3]. The achievable market price for lignin-based products mainly depends on the chemical or material substituted which, in turn, depends on the final utilization path. However, in most cases, lignin targets the replacement of fossil-based feedstock; therefore, the crude oil prices serve as the primary reference. These study findings evoked the question of whether it is sufficient to earn money with technical lignin without considering sustainability-related aspects, such as the negative environmental externalities of crude oil. Technical lignin utilization requires the consideration of additional aspects, because it is part of a transition towards a circular bioeconomy in a coupled social-ecological system [91]. These aspects include an investigation of appropriate policies and instruments (e.g., economic incentives, carbon taxes), further research efforts (e.g., on sustainability issues, markets, technologies), and efficient resource planning [92, 93].

While cost-revenue considerations are clearly in line with what is considered as neo-classical economics (e.g., perfect markets, profit maximization), socio-economic perspectives based on modern economic theory need to be taken to create a more holistic understanding of the underlying innovation processes. Transaction costs, such as those incurred by ensuring the security of supply [79], switching costs [81], or information asymmetries [78••] also explain why the effective commercialization of lignin lags behind. Only seven papers were identified in our review that clearly contribute to this research stream in the lignin area. Most of these indicate that the regulatory or market pull is not (yet) a driver in the overall innovation process. Until now, lignin researchers have focused mainly on internal (direct) factors that influence the success of commercialization (e.g., improving technology, performance, reducing costs, optimizing processes) while paying little attention to external (indirect) factors (e.g., substitution markets, demands, regulatory issues). However, fostering a circular forest-based bioeconomy that is profitable, environmentally favorable, innovative, technically feasible, and socially desirable is a challenge [93]. Innovation tends to follow a nonlinear, iterative process that often involves numerous individuals and organizations (such as industry, academia, different levels of government, NGOs, and civil society) [94, 95]. Therefore, more holistic approaches, such as the integration of internal and external factors by means of taking a systems approach [see, for instance, 96], need to be taken to move beyond the current focus on isolated and technological aspects of the bioeconomy transition pathways [91, 94].

Bauer et al. [94] reviewed the topic of innovation systems for biorefineries. They stated that the conditions for types of biorefinery products other than the predominant biofuels, and especially higher value products, are not yet well-understood,

pointing out numerous gaps in the scientific literature. These gaps include the roles of policy strategies and instruments, consumer preferences, legitimacy, and social acceptance. In addition, the authors stated that case studies (both successful and unsuccessful cases) could help researchers to gain valuable insights into, e.g., the relevance of organizational trust and networks in biorefinery development [94]. It is necessary to collaborate in networks and form partnerships across sectors, as well as involve public and private actors, to include a greater variety of industries and products in biorefinery development [94, 97]. With regard to the lignin research area, for instance, the perspectives of additional decision-makers (e.g., policy makers, consumers) could be of interest, as these have not yet been stressed in underlying studies on lignin. Researchers who applied a Delphi-study approach to survey European pulp and paper industry experts concluded that cross-sectoral partnerships will play a major role in developing new products in the European pulp and paper industry and predicted major changes in the future products [98]. Forest companies could benefit from cooperation with sectors that have a more positive demand outlook, including potential benefits such as increased competitiveness and environmental sustainability [98, 99]. However, cross-sector collaboration still presents major challenges [99]. The importance of cultivating an open-minded organizational culture and supporting collaboration was emphasized by Näyhä and Pesonen [100], whereby the main barriers identified to transforming the forest industry towards the biorefining business were related to the conservative organizational culture and lack of financial resources.

Mastering global challenges, such as climate change, requires actors and stakeholders to make changes not only in the niches but also in the socio-technical system. Therefore, even if the lignin- and other biorefinery niche-innovations are successful, and changes at the landscape level place pressure on the current socio-technical system, windows of opportunity must be used to achieve breakthroughs on mainstream markets [82].

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Compliance with Ethical Standards

Conflict of Interest Julia Wenger, Verena Haas, and Tobias Stern declare that they have no conflict of interest.

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