Economic and competitive potential of lignin-based thermoplastics using a multicriteria decision-making method

CÉDRIC DIFFO TÉGUIA, NIMA GHAVIDEL MEHR, WOLFGANG G. GLASSER, AND PAUL R. STUART

ABSTRACT: As a result of new lignin extraction plants hatching and increasing volumes of technical lignin becoming available, a variety of lignin derivatives, including phenolic resins and polyurethane (PU) foams, are reaching the marketplace or being used as intermediate products in many industrial applications. In the spectrum of possible lignin derivatives, thermoplastics appear particularly attractive due to a symbiosis of market, policy, and technology drivers.

To assess the preferredness for lignin-based thermoplastics, this paper adapted a risk-oriented methodology formerly applied to assess lignin usage in various applications (phenol-formaldehyde [PF] resins, PU foams, and carbon fiber applications) to the case of lignin-based thermoplastics using hydroxypropylated lignin (HPL) and miscible blends of lignin and polyethylene oxide (PEO). The HPL is considered for garbage bags and agricultural films applications, while lignin-PEO blends are used as replacement for acrylonitrile butadiene styrene (ABS) in applications such as automotive parts. In the methodology, two phased-implementation strategies were defined for each thermoplastic derivative, considering perspectives for profit maximization (90 metric tons/day integrated units) and revenue growth (350 metric tons/day overall capacity), which were considered for implementation within a softwood kraft pulping mill. A set of six criteria representative of the main economic and market competitiveness issues were employed, and their respective importance weights were obtained in a multicriteria decision-making (MCDM) panel.

Early-stage techno-economic estimates were done as a basis for the calculation of decision criteria. Compared to product derivatives previously assessed, capital investment for thermoplastic strategies appeared marginally higher due to the required lignin modification steps (on average 30% higher at similar capacity, and 6% for higher-scale revenue diversification strategies). Higher operating costs were also observed due to increased chemical expenses for all thermoplastic strategies, which are ultimately balanced by revenues associated with targeted thermoplastic products, leading to greater annual margins and cash flow generation over the project lifetime for thermoplastic strategies compared to other product applications (58% to 66% higher on average, at similar scale). Benefits of improved economics were reflected in economic criteria, internal rate of return (IRR), and cash flow on capital employed (CFCE), as well as in the price competitiveness criterion, CPC. Overall, the combination of relatively high lignin content in the plastic formulation and the less costly modification method contributed to lignin-PEO strategies, gaining the top two rankings. Based on their overall scores, both strategies defined for HPL would also integrate the group of "preferred" strategies, but are outranked by strategies that consider lignin positioning on PU foam applications.

Application: This paper highlights the market and technical drivers for the use of lignin in bio-based thermoplastic products such as garbage bags, agricultural films, and automotive parts. Additionally, the potential preference for such applications is assessed against phenolic resins and polyurethane foams previously studied, using a multicriteria approach.

Mismanaged single-use plastics pose multiple threats to the economy (e.g., tourism, fisheries, agriculture) and human health (e.g., water and food chain contamination), and perhaps most importantly, they pose threats to the environment (e.g., ocean and land pollution, loss of biodiversity) [1]. Regulatory measures such as bans and levies have been applied in more than 60 countries, with scopes varying from one geographical area to another. For instance, various incentive mechanisms exist in many European countries to encourage a broader use of bioplastics; lightweight plastics are increasingly banned at the state or city level in North America; and many African countries enforce a complete ban on the production and use of plastic bags [2]. Apart from regulations, more efficient waste management systems and a full transition to a circular economy can substantially reduce the pollution caused by single-use plastics [3]. Nonetheless, while such efforts can considerably contribute to pollution reduction, the current production of bioplastics remains as low as 1% of total plastic consumption [4].

Bioplastics, in general, include one or a combination of bio-based, biodegradable, or compostable plastic materials.

Bio-based plastics, as opposed to fossil-based plastics, originate from renewable resources such as first or second-generation biomass [5]. Although they generally degrade in nature, not all bio-based plastics are recognized as biodegradable from a regulation standpoint. Indeed, distinctions are made between biodegradable and compostable plastics based on the level of degradation after a given time period when exposed to naturally occurring microorganisms. This situation is highlighted by different standards; for example, in the United States, there are ASTM D6400-12 "Standard specification for labeling of plastics designed to be aerobically composted in municipal or industrial facilities" and ASTM D6868-17 "Standard specification for labeling of end items that incorporate plastics and polymers as coatings or additives with paper and other substrates designed to be aerobically composted in municipal or industrial facilities," and in Europe, there is EN 13432:2000 "Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation criteria for the final acceptance of packaging."

Even though the concept of biodegradability has received considerable attention in past decades, major concerns remain regarding the environmental impact of bioplastics leakage into natural systems [6]. Furthermore, current technology and end-life infrastructure prohibit plastics from being both recyclable and biodegradable/compostable, and therefore one characteristic has to be favored in the design phase. Since composting and biodegradation generate low-value products such as water and carbon dioxide (CO_2), recyclability is often more desirable, as it retains the plastic material in the economy [7]. Benefits from both properties can be combined in a manner similar to efforts made by Avantium and BASF in developing polyethylene furanoate (PEF), a bio-based recyclable material to substitute for polyethylene terephthalate (PET), which is petroleum based [8,9].

From a market standpoint, the rationale for bioplastics is closely linked to their scale-up potential and to expected environmental benefits. The global production of plastic materials was more than 360 million metric tons in 2020 and remained quite stable despite the COVID-19 pandemic, with most plastics being used in the packaging business (approximately 40%), followed by building and construction [10]. The demand is greatest for polypropylene (PP), polyethylene (PE), and polyvinyl chloride (PVC), of which around 29 million metric tons were consumed in Europe alone [10]. Acrylonitrile butadiene styrene (ABS) is expected to become one of the most attractive markets in the plastics industry, as it is the largest volume engineering thermoplastic resin and a key player in the segments of appliances and electronics, as well as automotive parts [11]. The global ABS market was estimated at around US$25B in 2019, with a compound annual growth rate (CAGR) of about 7% between 2020 and 2027 [12]. Although polyurethane (PU) and PP are the most widely used plastic polymers in the automotive industry, ABS is expected to experience fast growth due to its suitability in the manufacture of parts that need resistance to chemicals, such as shrouds, pipes, and electronic housings [13-15]. Therefore, it represents a promising opportunity to commercialize larger volumes of bio-based materials in coming years. Bio-based plastics could also have an important position in the segment of personal protective equipment, where they are preferred as a means to avoid plastic waste pollution related to single-use applications, such as medical gloves [16]. Furthermore, bio-based plastics address a continued rise in demand for compostable and biodegradable bags used in shopping and waste collection applications [17].

EVOLUTION OF THE LIGNIN FIELD TOWARDS THERMOPLASTICS

One of the main factors that still hinders the use of bioplastics is the production cost, which is primarily dictated by the feedstock expense, e.g., sugars or starches [18]. In this context, fibrous materials and lignin can play a major role in overcoming this challenge while addressing the issue of sustainability [19]. Lignin, in particular, is the second most abundant biopolymer after cellulose and constitutes approximately 30% of non-fossil carbon in the biosphere [20]. In recent years, implementation of new lignin extraction technologies by pulp and paper companies such as Domtar (Plymouth, NC, USA), Stora Enso (Sunila, Finland), and West Fraser (Hinton, AB, Canada) has significantly increased availability of technical lignins. In addition, with the recent lignosulfonates installation by Borregaard, the LignoTech plant in Fernandina Beach, FL, USA, the capacities of new units range from nearly 10,000 to 150,000 metric tons/year [21-24]. Major South American pulp and paper producers such as Klabin and Fibria-Suzano are also embarking upon lignin production at pilot and commercial scale, leveraging different types of biomass and hence different lignin structures [25,26]. From a market perspective, the global size of the lignin market is estimated at approximately US$794M with an annual growth rate of 1.9% from 2019 to 2025 [27], which demonstrates the considerable potential in this area.

In such a dynamic economic environment where there is a competitive race to access markets for lignins, the need for consistently delivering high-quality lignin products is crucial. Providers of lignin extraction technologies endeavor to increase their process efficiency, as well as deliver high-grade products with low impurity levels. For example, the VTT Technical Research Centre of Finland has developed the CatLignin process that is able to produce a highly-reactive catechol-rich lignin that could surpass phenol replacement levels for phenolic resin production above 50% without chemical modification [28]. Furthermore, the biotechnology company MetGen provides a controlled enzymatic process that oxidizes and fractionates lignin and yields a product aiming at high-value applications [29,30].

In this regard, Valmet has tailored and optimized its trademarked LignoBoost process in order to focus research towards different lignin end-markets [31]. Nevertheless, one of the major challenges in the commercial production of lignin is to maintain a consistent quality over time, mainly due to feedstock and process variations [32]. This could be addressed by a better stabilization of process operations once the lignin extraction unit is implemented, as lignin has a quasi-invariable structure in wood [33]. Even though lignin remains primarily used as an energy source in existing mills, several added-value applications have been developed in recent years [34,35] as a result of research and development efforts mainly pursued by pulp and paper companies, but also by biochemical industrial players. For example, Stora Enso and UPM have successfully incorporated lignin in the production of phenolic resins for the wood products industry [36,37], while the USDA's Forest Products Laboratory has played a significant role in the development of lignin-based carbon foams [38]. Also, lignin-based water barrier coatings have already been commercialized [39], along with other efforts to promote lignin use in thermoplastic applications such as compostable bags [40] and engineered parts for musical instruments or design objects [41,42]. In addition to Valmet's and Biochemtex's collaboration in the development of bio-PET incorporating lignin [43,44], the Natural Research Council of Canada (NRC) is actively developing lignin-based composite and plastic products, including PU foams [45,46] and lignin thermoplastic pellets using various resins [47].

PROCESSES FOR THE PRODUCTION OF LIGNIN-BASED THERMOPLASTICS

Due to the presence of various functional precursors in lignin polymer chains, most lignin-based polymeric materials, such as resins and foams, bear a highly cross-linked nanostructure. The large amount of lignin potentially available at commercial scale as a bio-based aromatic precursor, together with its sustainability, cost-effectiveness, and biodegradability, have attracted increasing interest for developing lignin-based thermoplastics as alternatives for petroleum-based products [48]. On the other hand, obtaining high-performance thermoplastics using lignin is challenging due to its relatively low molecular weight, high polydispersity, and rigidity [49].

To alleviate the previously noted obstacles, as well as to improve the thermoplasticity, processability, thermal stability, and mechanical properties of lignin, various methods can be considered. Those include plasticization, blending with polymers with low glass transition temperatures (Tg), and chemical modifications. These methods are known to reduce the natural Tg of lignin, which is in the range of 90°C to 170°C [48]. Plasticization of hardwood and softwood lignin using agents such as water, ethylene glycol, or lactic acid improves the mobility of lignin chains by increasing the free volume in the matrix [50]. Mixing lignin with synthetic polymers in miscible blends using polyethylene oxide (PEO), PET, or poly(N-vinyl pyrrolidone) (PVP), for example, has proven promising for forming a compound with a Tg lower than that of lignin. It has been used, for instance, in the production of lignin-based carbon fibers [51,52]. Chemical modification techniques, including esterification (e.g., acetylation), etherification (e.g., hydroxypropylation), grafting, and copolymerization help to mask the reactive hydroxyl groups on the lignin polymer chain, thus hindering its thermosetting properties [53-56]. Among lignin modification methods, hydroxypropylation as applied by Cao et al. [57] and lignin-polymer blending using PEO as applied by Akato et al. [58] are among the most advanced.

In order to produce a dry hydroxypropylated lignin (HPL) powder, lignin obtained from precipitation in a kraft process is dissolved in a sodium hydroxide (NaOH) solution to neutralize its acidic functional groups, then made to react with propylene oxide (PO) at pH in a range between 10 and 12.5. Thus chemically-modified lignin is further processed with an aliphatic polyester (e.g., polylactic acid, PLA) or an aromatic polyester (e.g., polybutylene adipate/terephthalate, PBAT) to produce film products such as trash bags and agricultural films, or injection molded products such as flower pots or toys [57]. Using that method, Glasser et al. produced HPL-based polymer blends with enhanced biodegradability and mechanical properties satisfying performance standards up to a 25%–30% lignin content [59].

While assessing lignin incorporation into composites for automotive parts, Akato et al. [58] used PEO as an interfacial adhesion promotor, taking advantage of hydrogen bonding between PEO ether linkages and lignin phenolic and aliphatic hydroxyl groups. Using that approach, blends of methanol-fractionated softwood kraft lignin and PEO (10% of lignin content in weight) were added up to 30% weight content in ABS formulation with no deleterious impact on mechanical properties. In contrast with HPL, which is a uniform substance once chemically modified, blends of lignin and PEO would form a solution with limited miscibility. Nonetheless, the method was demonstrated to also work with organosolv lignin, and it is considered promising for producing a performant and cost competitive bio-based ABS replacement.

RISK ASSESSMENT OF LIGNIN BIOREFINERY STRATEGIES

In light of the state-of-the-art regarding possible lignin derivatives, it is critical for potential implementers of lignin extraction technologies to assess the benefits and limitations of different product strategies. For that matter, a multi-perspective risk-oriented approach has been suggested to assess emerging biorefinery product-process options [60], which has been successfully used in the context of a pulp and paper mill considering a lignin-based biorefinery to produce phenolic resins, PU foams, or carbon fibers [61].

Category	Criterion	Interpretation
Economic Risk	Internal rate of return (IRR)	Measure of **project profitability under normal market conditions**, considering all phases of the biorefinery strategy. A hurdle rate can be set at 20%, considering the risk level expected in Year 5 of the project.
	Cash flow on capital employed (CFCE)	Ability to generate cash flows from the capital investment over the life of the project, and thereby to **improve the value of the company by lowering its debt**.
Market Risk and Competitiveness	Revenue diversification (RD)	Potential to meet revenue growth targets from new bioproducts, over the revenue from the mill in its current situation. It indicates an ability to mitigate market risk by being **less dependent on pulp sales, due to a more diversified source of revenues**.
	Competitiveness on production costs (CPC)	Robustness of the biorefinery strategy relative to an **aggressive price-cutting strategy from the competition**, based on assumptions of a low-end production price for the competition.
	Resistance to energy and chemicals market uncertainty (RECMU)	Vulnerability of the strategy to **production cost volatility due to the volatility of feed material costs** (product transportation and logistics not included).
	Robustness to poor market conditions (RPMC)	Ability to **afford process operation under poor market conditions** for a 6-month period, expressed by EBITDA* as a percentage of the capital investment.

* EBITDA = earnings before interest, taxes, depreciation, and amortization.

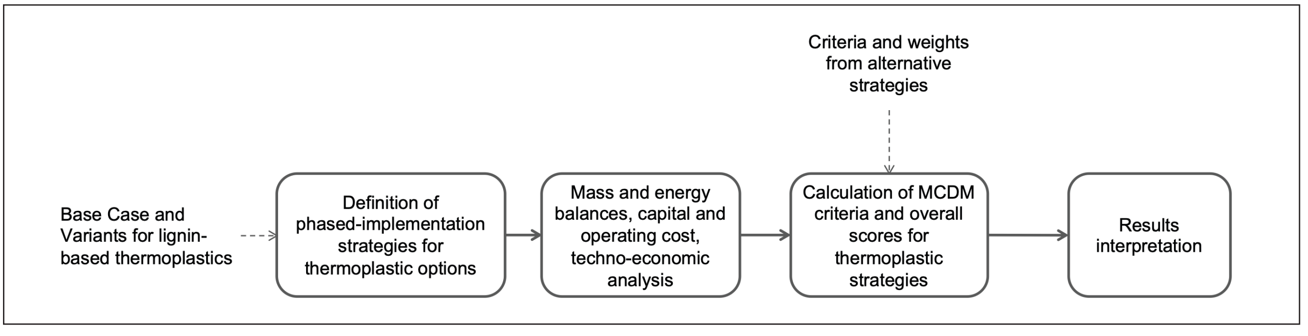
I. Decision criteria and agreed-on interpretation for evaluation of lignin strategies.

In this approach, a phase-implementation strategy is defined for each product-process combination with the purpose of mitigating specific risks, considering value chain penetration as well as market and technology uncertainties. Residual risks that are not addressed via the phased implementation are therefore highlighted and translated into decision criteria used in a multicriteria decision-making (MCDM) panel to identify preferred strategies. Early-stage techno-economic estimates are obtained using a large-block analysis and further used for the calculation of MCDM criteria. In the study conducted by Diffo Téguia et al. [61], six criteria (**Table I**) representing economic and competitiveness problematics were used to assess the set of strategies defined. Criteria selection followed a two-step approach to achieve a set of important criteria (as evaluated individually) [62], forming a consistent family (as evaluated as a whole) [63]. It then constitutes a pertinent basis to assess other lignin product derivatives, such as thermoplastics, which were not considered in that study.

Given the current context of emerging lignin-based thermoplastics and recent progress of lignin modification technologies, this paper aims to assess the attractiveness of thermoplastic derivatives under economic and market competitiveness perspectives, taking other pertinent lignin derivative products as benchmark.

METHODOLOGY

The methodology developed for this study leverages the assessment performed in [61], in order to provide a comparable basis between lignin-based thermoplastics and other lignin derivatives. It is slightly adapted to consider thermoplastic options, as shown in **Fig. 1**, especially regarding the definition of strategies and the pricing basis for techno-economic estimates.



1. Methodology to assess the preference for thermoplastics among lignin derivatives.

DEFINITION OF STRATEGIES FOR THERMOPLASTIC OPTIONS

The context foundation remains the implementation of a lignin biorefinery within a 1500 air dried (a.d.) metric tons/day kraft softwood pulp mill, where a 30 bone-dry (b.d.) metric tons/day lignin precipitation unit is running. Strategies are defined within (1) profit-oriented and (2) revenue-oriented perspectives, following a phased-implementation approach. For this study, the distribution of lignin derivatives in the portfolio is done in a manner that emphasizes the production of thermoplastics, with the objective to fully benefit from higher market demand compared to other lignin derivatives considered. Four new strategies have been defined, the detailed descriptions of which are provided in the next section and summarized in **Table II** for the group of profit-oriented strategies and in **Table III** for the group of strategies seeking revenue growth.

In a way consistent with strategies formerly defined, lignin is sold as an intermediate product; for example, to a plastic compounder or an end-product manufacturer. This study focuses on two thermoplastic alternatives, resulting either from the hydroxypropylation of lignin (referred to as hydroxypropylated lignin, HPL) or from the blending of lignin with PEO (referred as lignin-PEO blends). It is considered that HPL is commercialized for garbage bags and agricultural mulch films applications, while lignin-PEO blends are commercialized as an ABS replacement.

The definition of strategies is agnostic of lignin quality, in terms of the fact that it considers that lignins extracted either from kraft or from solvent pulping (SP) processes would result in satisfying product properties and performances. The integration of an HPL unit into the lignin precipitation process is inspired from Glasser et al. [59] and is illustrated in **Fig. 2**, where the lignin cake after one stage of precipitation and filtration and without acid washing (the lignin cake would be around pH 10) is fed to a

Lignin Biorefinery Strategies	Phase 0 Year 0 – Year 4	Phase I Year 5 – Year 9	Phase II Year 10 – Year 30
Base case 30 metric tons/day lignin precipitation	•Year 0: 100% lignin burned •Year 1: 28 metric tons/day burned, 2 metric tons/day to board mills •Year 2: 24 metric tons/day burned, 6 metric tons/day to board mills •Year 3: 18 metric tons/day burned, 6 metric tons/day to board mills, 6 metric tons/day to PF resin market	•Year 4: 12 metric tons/day burned, 6 metric tons/day to board mills, 12 metric tons/day to PF resin market •Year 5: 6 metric tons/day burned, 6 metric tons/day to board mills, 18 metric tons/day to PF resin market •Year 6+: 6 metric tons/day to board mills, 24 metric tons/day to PF resin market	
Ligno 90•PF	Same as Base Case	Increase of lignin precipitation capacity to 90 metric tons/day •Year 5: 6 metric tons/day burned, 6 metric tons/day to board mills, 48 metric tons/day to PF resin market •Year 6: 6 metric tons/day to board mills, 84 metric tons/day to PF resin market	
Ligno 90•PF PU	Same as Base Case	Same as Ligno 90•PF, except: •Year 5: 33 metric tons/day to PF resins, 15 metric tons/day to PU foams •Year 6: 54 metric tons/day to PF resins, 30 metric tons/day to PU foams	
Ligno 90•PF CFs	Same as Base Case	Same as Ligno 90•PF, except: •Year 5: 33 metric tons/day to PF resins, 15 metric tons/day to CFs •Year 6: 54 metric tons/day to PF resins, 30 metric tons/day to CFs	
Resin 90	Same as Base Case	Same as Ligno 90•PF	Acquisition of a resin producer •Year 10: 290 metric tons/day of resin produced •Year 11: 435 metric tons/day of resin produced
Ligno 90•PF HPL	Same as Base Case	Same as Ligno 90•PF, except: •Year 5: 24 metric tons/day to PF resins, 24 metric tons/day to HPL •Year 6: 24 metric tons/day to PF resins, 60 metric tons/day to HPL	
Ligno 90•PF Lignin-PEO	Same as Base Case	Same as Ligno 90•PF, except: •Year 5: 24 metric tons/day to PF resins, 24 metric tons/day to Lignin-PEO •Year 6: 24 metric tons/day to PF resins, 60 metric tons/day to Lignin-PEO	

PF = phenol-formaldehyde; PU = polyurethane; CFs = carbon fibers; HPL = hydroxypropylated lignin; PEO = polyethylene oxide.

II. Implementation phases of profit-oriented strategies.

<table>
<tr><th>Lignin Biorefinery Strategies</th><th>Phase 0
Year 0 – Year 4</th><th>Phase I
Year 5 – Year 9</th><th>Phase II
Year 10 – Year 30</th></tr>
<tr><td>Base case 30 metric tons/ day lignin precipitation</td><td colspan="3">•Year 0: 100% lignin burned
•Year 1: 28 metric tons/day burned, 2 metric tons/day to board mills
•Year 2: 24 metric tons/day burned, 6 metric tons/day to board mills
•Year 3: 18 metric tons/day burned, 6 metric tons/day to board mills, 6 metric tons/day to PF resin market
•Year 4: 12 metric tons/day burned, 6 metric tons/day to board mills, 12 metric tons/day to PF resin market
•Year 5: 6 metric tons/day burned, 6 metric tons/day to board mills, 18 metric tons/day to PF resin market
•Year 6+: 6 metric tons/day to board mills, 24 metric tons/day to PF resin market</td></tr>
<tr><td>Ligno 90 + SP•PF</td><td rowspan="5">Same as Base Case</td><td>Increase of lignin precipitation capacity to 90 metric tons/day
•Year 5: 6 metric tons/day burned, 6 metric tons/day to board mills, 48 metric tons/day to PF resin market
•Year 6: 6 metric tons/day to board mills, 84 metric tons/day to PF resin market Solvent pulping demo plant[1]</td><td>Increase of SP to full capacity[2]</td></tr>
<tr><td>Ligno 90 + SP•PF PU</td><td colspan="2">Same as Ligno 90 + SP•PF, except lignin distribution:
6 metric tons/day to board mills, 220 metric tons/day to PF resins, 124 metric tons/day to PU foams</td></tr>
<tr><td>Ligno 90 + SP•PF CFs</td><td colspan="2">Same as Ligno 90 + SP•PF, except lignin distribution:
6 metric tons/day to board mills, 220 metric tons/day to PF resins, 124 metric tons/day to CFs</td></tr>
<tr><td>Ligno 90 + SP•PF HPL</td><td colspan="2">Same as Ligno 90 + SP•PF, except lignin distribution:
6 metric tons/day to board mills, 84 metric tons/day to PF resins, 260 metric tons/day to HPL</td></tr>
<tr><td>Ligno 90 + SP•PF Lignin-PEO</td><td colspan="2">Same as Ligno 90 + SP•PF, except lignin distribution:
6 metric tons/day to board mills, 84 metric tons/day to PF resins, 260 metric tons/day to Lignin-PEO</td></tr>
<tr><td colspan="4">PF = phenol-formaldehyde; PU = polyurethane; SP = solvent pulping; CFs = carbon fibers; HPL = hydroxypropylated lignin; PEO = polyethylene oxide.
[1] The demo plant extracts 9 b.d. metric tons/day of lignin from 50 b.d. metric tons/day of hardwood.
[2] There is a capacity ramp-up of the full-scale plant from Year 10-12, resulting in 220, 270, and 350 b.d. metric tons/day of lignin extracted.</td></tr>
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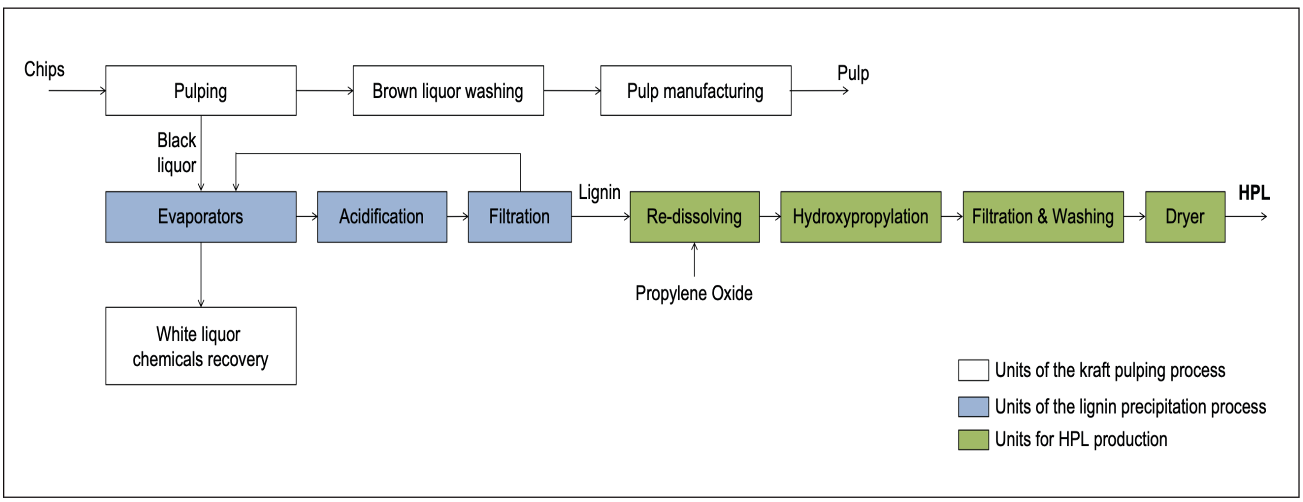
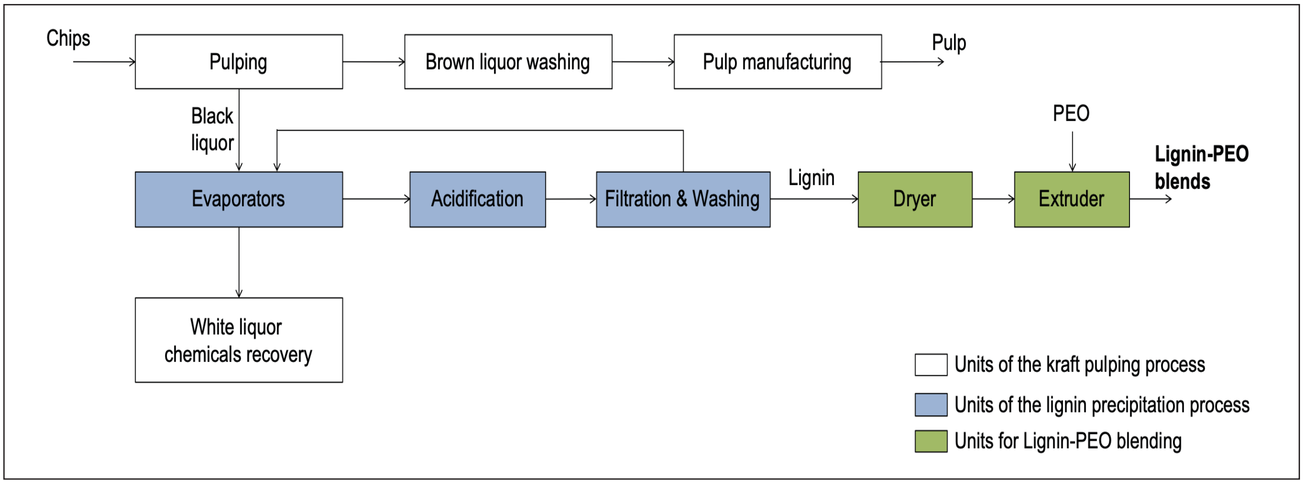
III. Implementation phases of revenue-oriented strategies.



2. Process configuration for the production of hydroxypropylated lignin (HPL) from lignin precipitation.



3. Process configuration for the production of lignin- polyethylene oxide (PEO) blends from lignin precipitation.

redissolving tank. The process configuration for lignin-PEO blends is inspired from Akato et al. [58] and illustrated in **Fig. 3**, where lignin exiting from the lignin precipitation or the SP process would be directly fed to the extruder, along with PEO.

TECHNO-ECONOMIC ANALYSIS

Information for mass and energy balances for HPL and lignin-PEO blends was collected from respective reference sources in the literature, and capital and operating cost estimates were achieved using a large-block analysis approach where process units shared with former strategies remained unchanged.

The main assumptions for thermoplastic strategies reside in basis for feed material unit costs and product prices. In this case also, costs for propylene oxide and polypropylene oxide were correlated with crude oil price using historical data, and estimated over the project lifetime considering a long-term average crude oil price of US$80/barrel [64,65]. For decision criteria using high-end feed material unit costs in their calculation, correlations were done with a long-term maximum crude oil price of US$150/barrel.

Since lignin-PEO blends are positioned as ABS replacement, its market price is also correlated with crude oil, with a long-term minimum crude oil price of US$55/barrel used to estimate the low-end market price for ABS. In the case

Feed Material, Product	Unit Cost, Product Market Price Estimates, US$/metric ton			Basis
	Nominal	Minimum	Maximum	
PO	1,365	-	1,540	• Correlation with crude oil price at US$80/barrel for the nominal values. • Low- and high-end values are correlated with crude oil prices of US$55/barrel and US$150/barrel, respectively.
PEO	1,425	-	1,730	
Lignin-PEO blends	2,550	2,180	-	
HPL	2,160	1,915 (mulch films) 1,680 (garbage bags)		• Correlation with corn price at US$3.8/bushel for the nominal value, using PLA as reference product. • Low-end market prices: PLA used as reference product for mulch films; LDPE used as reference for garbage bags, which is correlated with crude oil price at US$55/barrel.

PO = propylene oxide; PEO = polypropylene oxide; HPL = hydroxypropylated lignin; PLA = polylactic acid; LDPE = low-density polyethylene.

IV. Assumptions for feed material costs and product prices.

of HPL, since the main benefit of lignin is improving the plastic biodegradability, PLA is considered as the market reference both for agricultural mulch films and garbage bags. Therefore, the HPL price is correlated with the corn price, considering a projected long-term average corn price of US$3.8/bushel [66]. For criteria using low-end market prices, it is assumed that under poor market conditions, it would be more difficult to take advantage of the biodegradable aspect of garbage bags, for which it is less essential, compared to agricultural mulch films. Thus, low-density polyethylene (LDPE) is considered a more appropriate benchmark in such conditions, and its low-end price is estimated using correlations with crude oil price at US$55/barrel. The values obtained for feed materials costs and product prices are presented in **Table IV**.

DECISION CRITERIA AND SCORES FOR THE STRATEGIES

In addition to the techno-economic figure, the economic and competitiveness potential of thermoplastic strategies is assessed using the set of criteria in Table I. Although the consideration of additional criteria values relative to thermoplastic strategies could lead to a different appreciation of the relative importance of criteria, it is essential for the purpose of the comparison that preferences of project decision-makers, expressed through lower- and upper-bounds for the criteria as well as tradeoff values between them, are adequately represented. Therefore, utility functions and criteria weights from the previous study are reconducted and used to calculate overall scores for the strategies.

Indicator	Ligno 90• PF	Ligno 90• PF PU	Ligno 90• PF CFs	Resin 90	Ligno 90• PF HPL	Ligno 90• PF Lignin-PEO	Note/Comment
Lignin production capacity	90 metric tons/day	90 metric tons/day	90 metric tons/day	90 metric tons/day 435 metric tons/day resin	90 metric tons/day	90 metric tons/day	
Production rate by application	PF resin: 90 metric tons/day	PF resin: 60 metric tons/day PU foams: 30 metric tons/day	PF resin: 60 metric tons/day CFs: 30 metric tons/day	PF resin: 90 metric tons/day	PF resin: 30 metric tons/day Garbage bags: 39 metric tons/day Mulch films: 39 metric tons/day	PF resin: 30 metric tons/day ABS: 67 metric tons/day	Production rates for thermoplastic applications refer to lignin derivatives, i.e., after modification (HPL or blending).
Capital investment	US$ 32M	US$ 33M	US$ 39M	US$ 146M	US$ 46M	US$ 35M	Marginal variations due to equipment addition for lignin modification.
Annual operating costs (Phase II)	US$ 6M/year	US$ 7M/year	US$ 7M/year	US$ 104M/year	US$ 20M/year	US$ 14M/year	Added cost related to chemicals required for lignin modification.
Annual revenues (Phase II)	US$ 21M/year	US$ 41M/year	US$ 36M/year	US$ 287M/year	US$ 67M/year	US$ 67M/year	Product recipes lead to comparable revenues for the thermoplastic strategies.
Annual EBITDA (Phase II)	US$ 15M/year	US$ 34M/year	US$ 29M/year	US$ 183M/year	US$ 47M/year	US$ 53M/year	Despite higher costs, thermoplastic strategies generate greater margins.
NPV (Phases I and II combined)	US$ 17M	US$ 70M	US$ 49M	US$ 164M	US$ 79M	US$ 102M	Over the project lifetime, both thermoplastic strategies generate significant cash flows.

PF = phenol-formaldehyde; PU = polyurethane; CFs = carbon fibers; HPL = hydroxypropylated lignin; PEO = polyethylene oxide; ABS = acrylonitrile butadiene styrene; EBITDA = earnings before interest, taxes, depreciation, and amortization; NPV = net present value.
* Strategies descriptions are provided in Tables II and III.

V. Summary of techno-economic results for profit-oriented strategies.

BASE CASE AND VARIANTS

For each of the thermoplastic products considered, a phased implementation strategy has been defined following profit maximization and revenue growth perspectives. All strategies share a common Phase 0 similar with business-as-usual of the case study mill for the first six years, and a capacity increase of the lignin precipitation unit from 30 metric tons/day to 90 metric tons/day. For strategies *Ligno 90•PF HPL* and *Ligno 90•PF Lignin-PEO*, the amount of lignin dedicated to the PF resin application is capped at 30 metric tons/day, combining amounts used internally and sold over-the-fence, and all additional amounts are sold either as HPL or lignin-PEO blends (Table IV). It is considered that half of HPL is sold in the garbage bags segment, and the other half for agricultural mulch films.

In Group II for strategies involving SP, Phase I is similar for all strategies, and product diversification occurs in Phase II. For new strategies, *Ligno 90 + SP•PF HPL* and *Ligno 90 + SP•PF Lignin-PEO*, the amount of lignin dedicated to the PF resin application is capped at 90 metric tons/day, and all amounts of lignin resulting from solvent pulping are positioned on thermoplastic segments (Table III).

Indicator		Ligno 90 + SP•PF	Ligno 90 + SP•PF PU	Ligno 90 + SP•PF CFs	Ligno 90 + SP•PF HPL	Ligno 90 + SP• PF Lignin-PEO	Note/Comment
Lignin production capacity		350 metric tons/day					
Production rate by application		PF resin: 350 metric tons/day	PF resin: 226 metric tons/day PU foams: 124 metric tons/day	PF resin: 226 metric tons/day Carbon fibers: 124 metric tons/day	PF resin: 90 metric tons/day Garbage bags: 169 metric tons/day Mulch films: 169 metric tons/day	PF resin: 90 metric tons/day ABS: 290 metric tons/day	Production rates for thermoplastic applications refer to lignin derivatives, i.e., after modification (HPL or blending).
Capital investment	Total project cost	US$ 432M	US$ 438M	US$ 436M	US$ 470M	US$ 450M	Lower economies of scale with lignin-PEO due to the limited scalability of extruders.
	Company contribution	US$ 153M	US$ 156M	US$ 154M	US$ 164M	US$ 159M	
Annual operating costs (Phase II)	Total costs	US$ 123M/year	US$ 127M/year	US$ 126M/year	US$ 170M/year	US$ 145M/year	Added cost related to chemicals required for lignin modification.
	Company contribution	US$ 60M/year	US$ 62M/year	US$ 61M/year	US$ 85M/year	US$ 73M/year	
Annual revenues (Phase II)	Total revenues	US$ 222M/year	US$ 305M/year	US$ 284M/year	US$ 386M/year	US$ 388M/year	Higher market prices for thermoplastic derivatives magnify revenue increase at higher scale, compared to other strategies.
	Company share	US$ 120M/year	US$ 162M/year	US$ 151M/year	US$ 207M/year	US$ 208M/year	
Annual EBITDA (Phase II)		US$ 60M/year	US$ 100M/year	US$ 90M/year	US$ 123M/year	US$ 208M/year	Although the impact of single products tends to be diluted in the context of multi-product portfolios, the role of thermoplastic derivatives on margins improvement is significative.
NPV (Phases I and II combined)		US$ 6M	US$ 50M	US$ 37M	US$ 65M	US$ 80M	Since cash flow increase related to thermoplastics implementation occurs further in time (after Year 10), its impact on NPV is mitigated.

PF = phenol-formaldehyde; PU = polyurethane; CFs = carbon fibers; HPL = hydroxypropylated lignin; PEO = polyethylene oxide;
ABS = acrylonitrile butadiene styrene; EBITDA = earnings before interest, taxes, depreciation, and amortization; NPV = net present value.
* Descriptions of strategies are provided in Tables II and III.

VI. Summary of techno-economic results for revenue-oriented strategies.

RESULTS AND INTERPRETATIONS

Techno-economic assessment

The result of the techno-economic analysis is summarized in **Table V** for profit-oriented strategies, and in **Table VI** for revenue-oriented ones. In Table VI, the "company contribution" refers to the share of cost or revenues attributed to the forestry company under the joint venture assumptions considered for Group II strategies. In comparison with strategies leading to other lignin derivatives, thermoplastic-oriented strategies require marginally higher investment related to equipment for lignin modification, and higher operating cost due to chemicals consumption; NaOH and PO in the case of HPL, and PEO in the case of lignin-PEO blends. For both applications considered, the margin and NPV increase tend to provide a rationale for the higher cost.

Combined with the process configuration and the market price for targeted applications, the product formulation – 3:10 PO over dry lignin for HPL and 1:10 PEO over dry lignin for lignin-PEO blends on a weight basis – plays a distinguishing role between thermoplastic strategies. Lower lignin content and market price for HPL result in comparable revenues for both strategies; however, strategies leading to lignin-PEO blends benefit from lower chemical consumption and a simpler process, which result in a more significant margin creation.

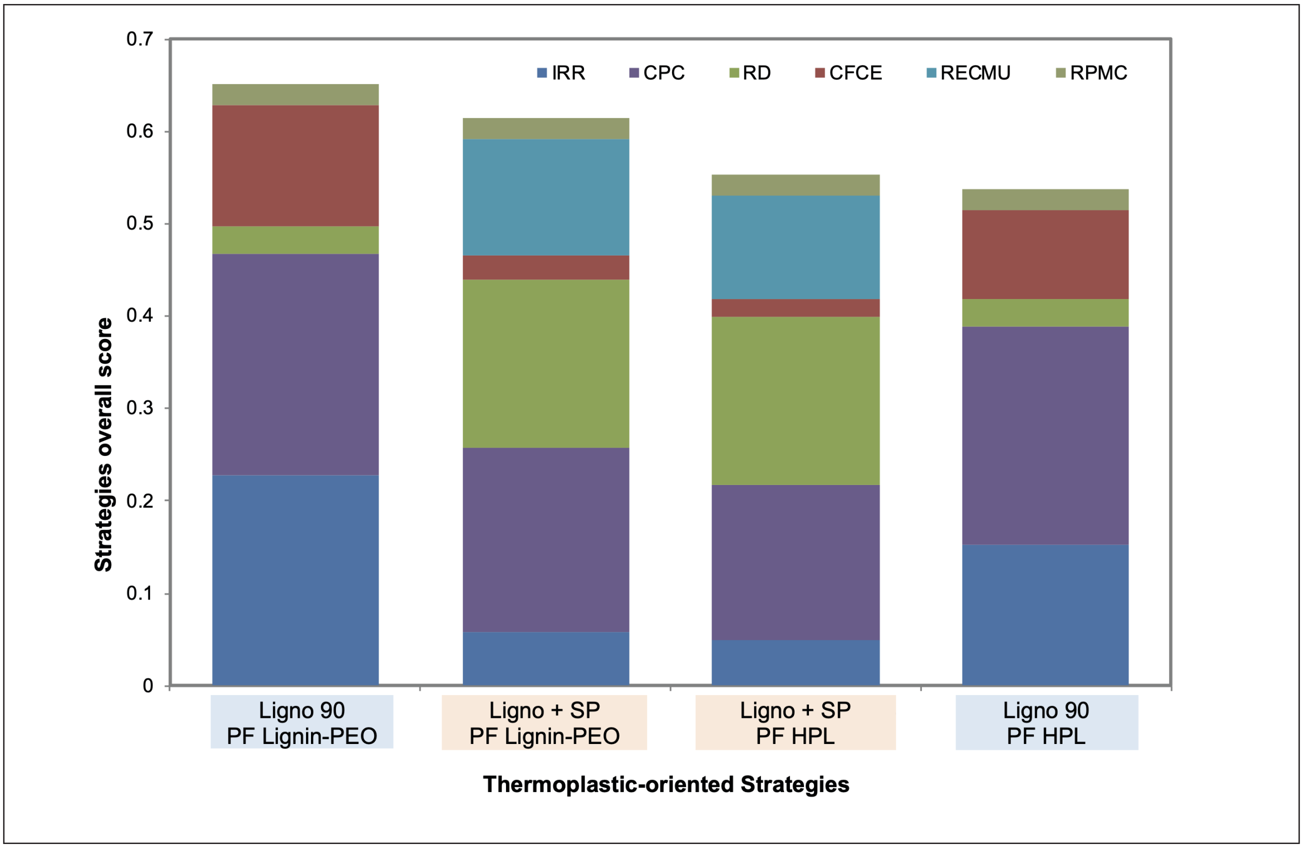
EVALUATION OF DECISION CRITERIA

Values obtained from the calculation of decision criteria for thermoplastic strategies are presented in **Table VII** and are put in perspective against the best-performing strategy leading to other lignin derivatives. They appear among top-performing strategies for all criteria, in a way that emphasizes respective strengths and differences between profit-oriented and revenue-oriented strategies. Both

Criterion*	Ligno 90• PF HPL	Ligno 90• PF Lignin-PEO	Ligno 90 + SP•PF HPL	Ligno 90 + SP• PF Lignin-PEO	Best-performing Among Other Strategies (Value)	Note/Comment
Internal rate of return (IRR)	48%	62%	29%	31%	Ligno 90•PF PU (57%)	Over time, margin increase satisfyingly balances the investment on lignin modification. HPL strategies are somehow disadvantaged by higher capital costs.
Cash flow on capital employed (CFCE)	3.6	5.1	1.5	1.7	Ligno 90•PF PU (4.5)	Lower investment requirements make the lignin-PEO strategy the most capital-efficient. In comparison, HPL is less efficient than the PU foam strategy.
Revenue diversification (RD)	10%	10%	63%	64%	Ligno 90 + SP•PF PU (51%)	At higher scale, the impact of thermoplastics on revenue increase is more significant.
Competitiveness on production costs (CPC)	64%	75%	45%	54%	Ligno 90•PF PU (65%)	The low-end market price for HPL as garbage bags makes it less robust compared to PU foams and ABS.
Resistance to energy and chemicals market uncertainty (RECMU)	19%	23%	65%	75%	Ligno 90 +SP•PF PU (83%)	Chemicals required to modify lignin make thermoplastic strategies more vulnerable to volatility than PU foams and CFs strategies.
Robustness to poor market conditions (RPMC)	31%	51%	21%	28%	Ligno 90•PF PU (22%)	Under poor market conditions, relatively higher market prices make thermoplastic strategies more robust than other strategies at similar scale.

PF = phenol-formaldehyde; HPL = hydroxypropylated lignin; PEO = polyethylene oxide; PU = polyurethane; ABS = acrylonitrile butadiene styrene; CFs = carbon fibers.
* Criteria definitions are provided in Table I, and descriptions of strategies in Tables II and III.

VII. Summary of criteria evaluation for thermoplastic strategies.



4. Overall scores for thermoplastic strategies. (Criteria definitions are provided in Table I, and descriptions of strategies in Tables II and III.)

profit-oriented strategies, *Ligno 90•PF HPL* and *Ligno 90•PF Lignin-PEO*, present high scores on economic criteria, as well as on price competitiveness. Capital costs related to lignin modification into HPL limit the profitability and capital efficiency of the strategy *Ligno 90•PF HPL*, which remains among the most cost competitive despite the low-end market price considered for garbage bags. Strategies seeking revenue growth, *Ligno 90 + SP•PF HPL* and *Ligno 90 + SP•PF Lignin-PEO*, are the best-performing regarding revenue diversification; however, they are more sensitive to fluctuations on feed materials markets compared to other revenue-oriented strategies that consume less chemicals.

UPDATED RANKING OF STRATEGIES

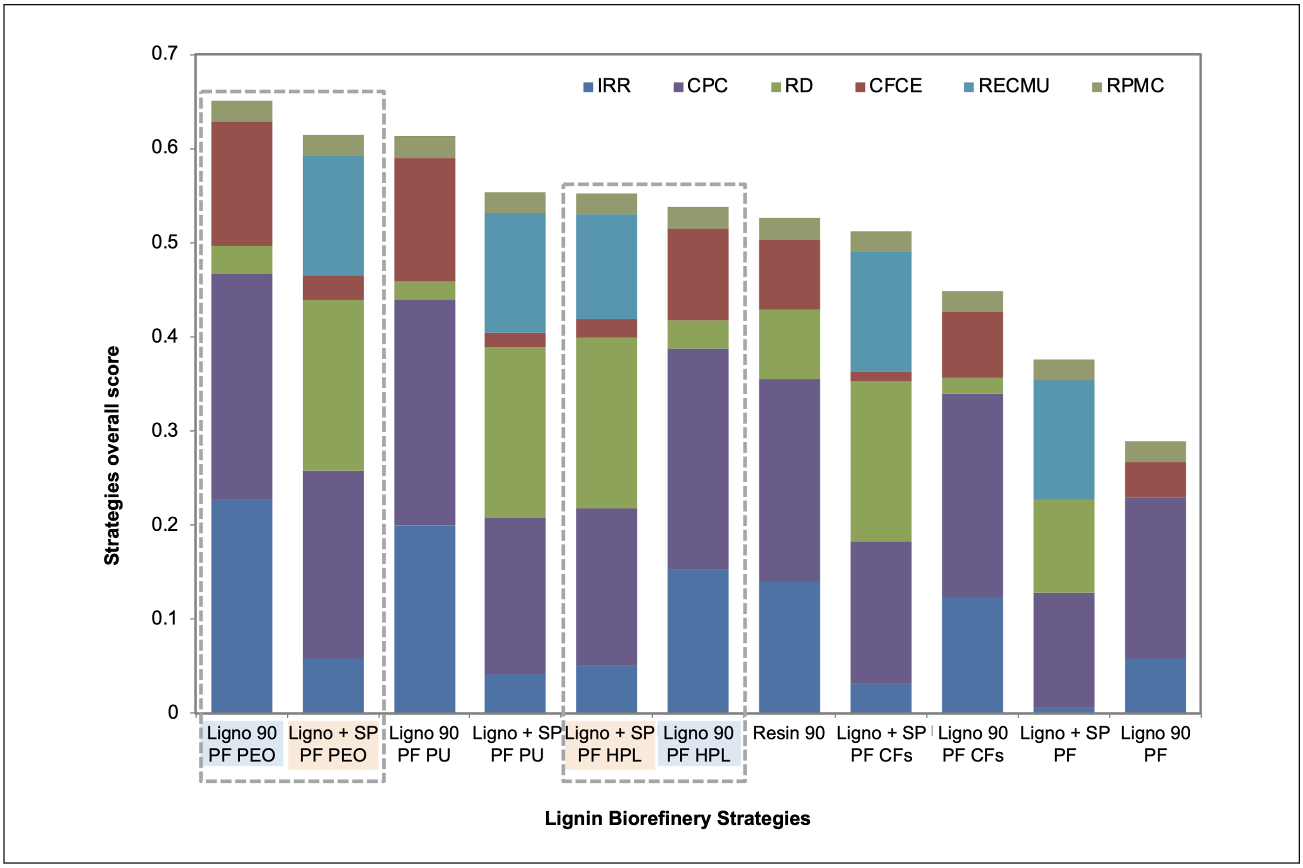
Overall scores obtained by combining criteria values with their respective weights are presented in **Fig. 4** for thermoplastic strategies, and in **Fig. 5** for the entire set of strategies. Scores for strategies leading to PF resin, PU foams, and carbon fibers are unchanged, and the overall picture is updated by the inclusion of scores for thermoplastic strategies.

Among thermoplastic strategies, those producing lignin-PEO blends appear as top-performing under both profit-oriented and revenue-increasing perspectives, due to a combination of economic and competitiveness advantages. There is a clear distinction between strategies at the 90 metric tons/day scale; however, strategies involving solvent pulping have closer scores (11% difference between revenue-oriented strategies compared to 21% difference between profit-oriented strategies). This is due to a lower influence of benefits associated with thermoplastics compared to higher capital and operating costs at that scale.

Interestingly, the profit-oriented strategy has the greater score among options producing Lignin-PEO blends, while it is the revenue-oriented strategy that performs better among options to HPL. Indeed, the limited scores for internal rate of return (IRR) and cash flow on capital employed (CFCE) disadvantage the *Ligno 90•PF HPL* strategy, while *Ligno 90 + SP•PF HPL* is favored by revenue diversification (RD) and resistance to energy and chemicals market uncertainty (RECMU). Nonetheless, strategies leading to PU foams remain better ranked than those leading to HPL. The overall performance of thermoplastic strategies might lead to questioning the vertical integration approach towards onsite PF resin manufacturing through strategy *Resin 90*, which was formerly identified among Preferred strategies but is out of the Top 6 in the updated ranking.

DISCUSSION

From **Fig. 5**, it can be interpreted that all thermoplastic strategies would integrate the group of Preferred strategies



5. Updated scores of strategies and rankings resulting from criteria evaluation. (Criteria definitions are provided in Table I, and descriptions of strategies in Tables II and III.)

formerly identified by project decision-makers. Lignin-based thermoplastics are promising derivatives; however, the ranking of strategies for PU foam production demonstrates that thermoplastics will not be preferred under all circumstances. Winning conditions for lignin-based thermoplastics could be interpretated as: (1) minimal requirements for lignin modification; (2) maximized lignin content in the plastic formulation for performances at least similar to competing products; and (3) a market application ideally not dependent on crude oil fluctuations, where a decent market price can be targeted.

Under assumptions considered in this study, the strategy towards lignin-PEO blends appears superior to others. Given projections for the demand on the ABS market (6% CAGR in 2018-2023), the risk can be considered moderate for the expectable return, especially if uncertainty on technology demonstration is addressed. Recent advancements from major players in the lignin sector tend to confirm ABS replacement as a one of the most promising segments. Nonetheless, HPL might become preferred in scenarios where policies make biodegradability mandatory for plastics usage, thus creating a higher market demand and a potential premium for such products.

Although only biodegradability has been highlighted in the case study, recyclability is another aspect of value proposition associated with bioplastics that is worth emphasizing when applicable. Recyclability is increasingly recognized as essential for the circular economy; therefore, validating that lignin integration into the plastic formulation does not negatively impact this characteristic becomes critical for market adoption.

Also, the preference for lignin-based thermoplastics over other derivatives is dependent on the assumption that kraft and Organosolv lignins are compatible with targeted applications. For example, the presence of unpleasant odors from plastic parts are potential showstoppers for the adoption of lignin derivatives in applications where the end-product contributes to the comfort of the user, such as for interior automotive parts. The ability and easiness to address important end-product characteristics might become distinguishing factors between lignin types. If for a given lignin type, additional efforts are required to make it more suitable, the impact of added capital and operating costs on criteria such as IRR and CFCE needs to be monitored.

From a business flexibility point of view, having access to several lignin types while implementing business phases over time provides the forestry company a stronger business model in which different lignin types can be dedicated to market segments more appropriately. One of the main challenges for a forestry company resides in the mitigation of the business risks that pursuing thermoplastic derivatives represents. While a vertically-integrated forestry company with an easier access to the PF resin value chain would better benefit from selling lignin as a phenol replacement in the short term to mitigate market risk before integrating the thermoplastics segment, a horizontally-integrated company can consider opportunities more broadly.

CONCLUDING REMARKS AND PATH FORWARD

Environmentally-friendly policies and market dynamics are among the drivers that make bioplastics one of main centers of interest as circular economies are being established. This creates favorable conditions for a larger commercialization of lignin-based thermoplastics in various segments where forest product companies can seize promising opportunities. The present study assessed the potential of lignin-based thermoplastics by adapting an approach used for identifying preferred strategies leading to PF resins, PU foams, and carbon fibers, based on a techno-economic analysis and the evaluation of a multi-disciplinary set of criteria. Thermoplastic applications assessed included HPL for biodegradable garbage bags and agricultural mulch films, and lignin-PEO blends for ABS replacement.

Techno-economic estimates showed that marginal capital investments were required to implement lignin modification techniques leading to desired thermoplastics and resulted in significant margin creation as compared to other lignin derivatives. The simplicity and cost effectiveness of the lignin modification process, the lignin content in the plastic formulation, and the market price for the targeted application appeared to play an important role in the economic return. The strategy for production of lignin-PEO blends at low volume obtained the highest overall score as a result of a combination of these factors.

Based on their scores and ranking, all strategies defined for thermoplastic derivatives would be considered among Preferred strategies, along with the strategies leading to lignin-based PU foams. In addition to the option *Ligno 90•PF Lignin-PEO*, that has the top rank, the two strategies involving thermoplastics at high scale appeared both competitive and robust and can further create business flexibility advantages through the horizontal integration of different lignin types into various market segments.

For lignin-based thermoplastics to be successful, the suitability of the lignin type and expected end-product performance for the targeted application must be validated, along with the definition of a strong value proposition. As regulations and policies evolve to support the establishment of a circular bioeconomy, there is increasing use of recycled plastic materials and a rising demand for biodegradable plastics. Lignin-based thermoplastics represent a unique opportunity for forestry companies to build strong competitive advantages from lignin, which improves the biodegradability of plastic blends where it is integrated. **TJ**

ACKNOWLEDGMENTS

The authors are grateful for the financial support received from the Program on Energy Research and Development (Project OERD-CEV-19-106) and the Forest Innovation Program of the Canadian Forest Service (CFS Biorefinery Flagship Project) at Natural Resources Canada. The authors would also like to thank academic partners in the project, Pauline D'Hollander and Pedro Fardim from KU Leuven (Belgium), and the industrial partner C12XL Technologies, that provided technical information and contributed to the validation of assessment results.

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ABOUT THIS PAPER

Cite this article as:
Diffo Téguia, C., Mehr, N.G., Glasser, W.G., et al., *TAPPI J.* 21(9): 479(2022). https://doi.org/10.32964/TJ21.9.479

DOI: https://doi.org/10.32964/TJ21.9.479

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

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ABOUT THE AUTHORS

Diffo Téguia

Mehr

Glasser

Stuart

There is growing interest for the definition of technology and business strategies to facilitate the development of the bioeconomy in general, and particularly in the forest sector. This includes the development of new bio-based products, such as lignin derivatives. The current study complements two papers we published in the March 2017 [59] and April 2017 [61] issues of *TAPPI Journal*.

The most challenging aspect of this research is related to the scarcity of viable market and cost information on bio-based plastics. To address this, the pricing and market penetration strategy has been defined based on products that the lignin-based plastics would substitute.

The significant discovery in this research is related to the extent at which lignin-based thermoplastics could be competitive compared to phenolic resin and polyurethane foam applications that are typically favored. Another interesting aspect of this research is that although lignin is generally appreciated for its thermoset properties (e.g., for adhesive applications), it can play an important role in thermoplastic resins, with the resulting product being competitive in multiple aspects when compared to other lignin derivatives.

The information published in this paper could help mills to: (1) define strategies for the development of lignin-based products to better valorize black liquor; (2) understand how phased implementation helps mitigate risks associated with such strategies; and (3) identify how existing lignin precipitation processes could be modified and/or rendered flexible for the production of multiple derivatives.

Although no continuation has been established for this research at the moment, it could be extended in multiple ways, including the application of the methodology to other lignin derivatives, its application to other bioproducts and bioeconomy development context, or the development of new decision criteria for different implementation cases in the pulp and paper sector.

Diffo Téguia and Mehr are process engineers at Natural Resources Canada, CanmetENERGY, in Varennes, QC, Canada. Glasser is professor emeritus, Sustainable Biomaterials, at Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. Stuart is professor in the Chemical Engineering Department at Polytechnique Montreal in Montreal, QC, Canada. Email Diffo Téguia at cedric.diffo@gmail.com.

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