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Cost structure of bio-based plastics: A Monte-Carlo-analysis for PLA

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Paper 197

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Abstract

This paper conducts a meta-analysis of the estimated costs of producing Polylactic Acid (PLA). Cost contributions of specific inputs and process stages are identified through a production chain perspective. By applying the Monte Carlo technique, uncertainties in current estimates are reflected, both regarding technological input requirements and the development of input prices. Moreover, results are compared between two scenarios differing in feedstock choice: production from corn grain and from corn stover. The results stress the specific importance of capital costs, energy, and the biological feedstocks as cost components. Nevertheless, the Monte Carlo simulations point out that the current state of knowledge is still subject to a high degree of uncertainty.

Keywords

Life Cycle Cost Analysis, bio-based plastics, PLA, plastic feedstocks, Monte Carlo Simulation

1 | Introduction

In the course of the transformation to a sustainable and circular bioeconomy, biobased and biodegradable plastics have gained increasing attention in recent years. The use of renewable instead of fossil raw materials is expected to have ecological advantages over conventional plastics in the form of a smaller carbon footprint and less intensive resource consumption. Moreover, the feature of biodegradability promises a solution to the increasingly pressing problem of plastic waste on land and in the sea. Therefore, the growing environmental awareness of consumers is strengthening the demand for bio-based and biodegradable plastics, while at the same time policy measures worldwide, but particularly, in Europe have supported the bioplastics industry. Nevertheless, according to estimates from the industry association European Bioplastics (2020), currently only about one percent of the more than 368 million tonnes of plastic produced worldwide are bio-based and/or biodegradable.

One of the main reasons for the limited market penetration is economics. Since plastic goods are largely standardized products such as packaging, price competitiveness plays a particularly important role. Bio-based plastics exhibit higher production costs than their fossil-based counterparts, especially in the segment of novel polymers that are interesting in terms of their biodegradability. In view of the complexity of the production processes, the reasons for this cannot be attributed from the outset to a particular input or technology. To better understand the market-side obstacles to the growth of the bio-based segment, representative estimates are therefore required. Unfortunately, the data situation in this respect is currently very limited. For example, there is currently no public database on the development of the average production costs of certain polymers at industry level. Existing estimates are usually based on individual technoeconomic case studies, the results of which are to a certain extent dependent on local production conditions and decisions regarding the use of specific feedstocks and technological setups. Therefore, to get an overview of the scattered data situation for individual polymers, meta-studies are required. In addition to the determination of a mean cost level, these should, if possible, also reflect the level of technological and market-related cost uncertainty in the existing estimates.

In this paper, we conduct such a meta-study for the polymer polylactic acid (PLA) based on current literature. PLA is currently the market leader in the segment of bio-based and biodegradable plastics, and at the same time the polymer that is generally estimated to come closest to conventional plastics in terms of its manufacturing costs. In addition to looking at the average cost pattern, we also seek to reflect the observed level of uncertainty by applying the Monte Carlo Technique. To acknowledge the current debate on the choice of feedstocks, we compare a scenario featuring corn grain as currently popular feedstock from the so-called first generation with a production scenario featuring corn

stover as an alternative second-generation feedstock. Finally, the framework is utilized for a discussion of future cost evolution by means of considering alternative long-term scenarios.

The remainder of the paper is structured as follows: Section 2 provides an introduction into the specific market situation for PLA. Section 3 discusses the results of existing life cycle cost studies on PLA production. Section 4 presents methodology and data basis of our own analysis. Section 5 presents results of the deterministic and stochastic analysis, while section 6 concludes.

2 | PLA - properties and market developments

The increasing interest in sustainable materials is reflected in the growing market for bio-based and biodegradable plastics. The latest market report from European Bioplastics 2020 shows steady growth in the bioplastics segment and indicates a global increase in bioplastics production capacity from about 2.11 million tonnes in 2020 to about 2.87 million tonnes in 2025. Currently, biodegradable plastics account for almost 60% of global bioplastics production capacity and will continue to grow faster than the bio-based and non-biodegradable plastics¹ segment in the coming years (European Bioplastics, 2020). Among biodegradable plastics, PLA has currently the largest market share and promises the strongest growth compared to the other biodegradable polymers.

PLA is a bio-based and biodegradable polymer built from lactic acid molecules. Being a thermoplastic polyester, it will soften when heated and harden when cooled. It can be cooled and heated several times without changing its mechanical and chemical properties. This allows the material to be shaped and processed by liquefaction and molding techniques and then recycled by similar processes. Due to its flexibility and other technical properties, PLA can technically compete with conventional plastics and is therefore suitable for a wide range of applications, from single used packaging to durable consumer goods. Among the different application segments, packaging is by far the largest market segment for PLA and shows the highest growth rates (European Bioplastics, 2020).

While PLA can compete with conventional plastics from a technical point of view, the prices of PLA cannot currently keep up with those of conventional plastics. The production costs of PLA significantly exceed the costs of producing fossil-based plastics. PLA production generally involves the following process steps: raw material extraction, glucose extraction, fermentation, and polymerisation (see Figure 1). The exact process

¹ Bio-based and non-biodegradable plastics include drop-in solutions such as bio-based PE (polyethylene) and bio-based PET (polyethylene terephthalate) as well as bio-based PA (polyamides) and currently account for just over 40 % of global bioplastics production capacity (European Bioplastics, 2020).

routes differ in the choice of biological raw materials used as a starting point in the production of these polymers. Depending on the starting material, different production steps and inputs are necessary, which in turn affects the cost structure.

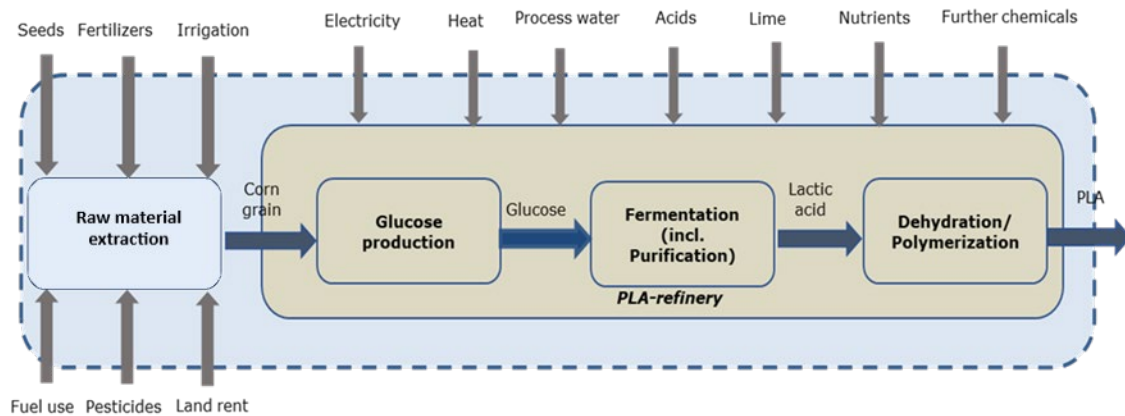


Figure 1: Process route of PLA-production based on corn grain (Source: own representation)

Feedstock choice is one of the central issues for PLA production also from an economic perspective, as it not only influences costs related to the primary stage of the life cycle, but also due to its technological implications for the bio-refinery. Depending on the feedstock, it can be costs associated with the cultivation of agricultural land, such as expenses for fertilisers, pesticides, energy for agricultural machinery and irrigation. The costs related to the extraction of the chemical feedstock from harvested agricultural products can also be of importance, depending on what kind of marketable by-products can be generated as a financial compensation.

Currently, corn and sugarcane are the dominant plant sources for PLA production, but a variety of innovative resources to produce lactic acid have also been under discussion. The main purpose of these development processes has been to overcome the environmental issues associated with land use and competition with food production that relate to the current feedstock generation of food crops. Among these, the use of residual plant material from the cultivation (e.g., stover) and processing (e.g., sugar cane bagasse) of these crops as cellulose-based feedstocks has already been discussed for quite a while. The fact that these materials are obtained as by-products prevents or at least mitigates the caveats against the first-generation feedstocks. Moreover, several suggestions have been made in recent year to decouple PLA production from agricultural land use completely. One strand of this literature focuses on the utilization of by-products and waste from the food industry which are otherwise of no or low economic value. Harbec (2010) and Broeren et al. (2017) analyse the use of wastewater accruing in the industrial processing of potatoes. Liu et al. (2018) investigate the production of lactic acid from cheese whey, with lactose and proteins as feedstocks. Juodeikiene et al. (2016) are assessing ways to improve the yield from cheese whey, by comparing different bacteria species

and enzymes used in fermentation. Nguyen et al. (2013) examine a scenario where waste from the industrial extraction of curcuminoid used in medical applications from the *curcuma longa* root is fermented to lactic acid through simultaneous saccharification and fermentation. De la Torre et al. (2018) consider a mixture of orange peel waste and corn steep liquor as substrates. Pleissner et al. (2016) investigate waste from coffee production, coffee pulp, as substrate. Alves de Oliveira et al. (2020) propose the use of sugar beet pulp obtained as a side product for animal feed from the process of extracting sugar from sugar beets. Another strand examines the potential to shift from land-based to sea-based resources. The cultivation and fermentation of sea plants rich in carbohydrates is seen as an opportunity to set up new production routes from scratch and thus preserve existing food production chains from being disrupted by plastic manufacturing. In this vein, Helmes et al. (2018) explore the use of the seaweed *Ulva spp.* in lactic acid production. Ögmundarson et al. (2020) experiment with the cultivation of brown algae of the species *Laminaria sp.* as feedstock source.

The level of production costs is therefore strongly dependent on raw material prices and technological progress in bioplastics production. In addition, production capacities and the associated economies of scale have an influence on unit costs. Political measures to promote sustainable alternatives to fossil-based plastics can support the expansion of production capacities for PLA. Furthermore, the development of prices for competing fossil-based plastics depending on the development of the crude oil price plays an important role in the development of demand for bioplastics and thus also for the expansion of production capacities.

3 | Studies on the costs of PLA production

In order to find the most relevant journal articles analysing the cost structure of PLA production, an extensive literature search was conducted. For this purpose, generally recognised search engines such as Google Scholar, ResearchGate and the libraries of relevant publishers of scientific journals were searched using search terms such as "PLA cost analysis", "PLA cost", "techno-economic analysis PLA" or "PLA LCC". It has been shown that despite the recent growing interest in the production of bio-based plastics such as PLA, there is a lack of studies in the literature that assess the cost structure and techno-economic feasibility of commercial production of PLA.

In this section, the most relevant studies for this paper are presented in detail. These five studies examine the costs of the individual process steps in PLA production. Due to different feedstocks considered for the production of PLA, the process routes investigated also differ between the studies. For this reason, the results are not directly comparable

with each other, but they do provide information on the cost structure and the approximate cost range for the production of PLA.

In an older study by Jim Lunt & Associates (2010), the manufacturing process of PLA produced from locally grown raw materials is examined to test its economic viability. By applying an engineering cost model based on engineering expertise and publicly available information, the study estimates the costs of manufacturing PLA in Maine (USA). Two different process routes are investigated, which differ in the choice of feedstock. One production route involves PLA production from potato starch, the other PLA production from sugar extracted from wood. The results of the cost analysis are compared with the current costs of PLA production from Midwest corn by NatureWorks.

The study identifies four major drivers for PLA costs. Firstly, raw material costs, which in the first case include the cost of dextrose, which is mainly obtained from potato processing waste, and in the second case costs of wood sugar. Secondly, additive and waste disposal costs, in particular the costs of chemicals, nutrients and gypsum waste associated with bacterial fermentation. The third cost driver is process revenue, and the fourth cost driver comprises utility costs, e.g., electricity costs.

The process routes are examined in three scenarios, which differ in capital costs and the technology used to produce PLA. In all the scenarios, a plant capacity of 50,000 tonne of PLA is considered. The first scenario, the "greenfield" scenario, requires the highest capital costs, as it assumes the construction of the plant from the ground up. The higher capital costs result from the provision of electricity, steam, and water systems in particular. In addition, this scenario assumes that the traditional bacterial fermentation process is used to produce lactic acid, which is a more expensive technology. The second scenario achieves significant cost savings (approx. 22%) compared to the first scenario, as it assumes a "brownfield" construction strategy. Compared to the "greenfield" scenario, this strategy not only reduces the capital costs and thus simplifies the financing of plant construction, but also lowers the annual operating costs, including taxes, insurance, maintenance, return on investment and other expenses. Similar to the first scenario, traditional bacterial fermentation technology is used here. The third scenario, the preferred one, achieves further significant cost reductions by using the new yeast fermentation technology while maintaining a brownfield construction strategy. Costs are 8% lower than in the other brownfield scenario and 29% lower than in the greenfield scenario. The cost structure of these processes is compared with the cost structure of the usual processes in which PLA is produced from Midwestern corn. The study concludes that by using advanced fermentation technologies and already existing industrial infrastructure, the considered scenario can compete with corn-based PLA.

Chiarakorn et al. (2014) investigate the production of PLA considering the Cargill Dow process by NatureWorks. In contrast to the study by the Jim Lunt & Associates (2010)

discussed earlier, the study by Chiarakorn et al. (2014) assesses environmental costs (indirect costs) in addition to financial costs (or direct costs such as production costs and investment costs). Two production scenarios for PLA are analysed. In the first scenario, cassava roots are used as raw material to produce PLA. Cassava starch is extracted from the cassava roots, which is then converted into glucose and finally into PLA. The second scenario omits the first steps and starts with the production of glucose from cassava starch and then continues as the first scenario. The calculations include the potential direct costs of PLA production, raw material costs (cassava roots and chemicals), capital costs, labour costs, operating costs, and waste treatment costs. The environmental costs (indirect costs) of PLA production include two main cost items: the cost of CH₄ emissions from wastewater and the cost of CO₂ emissions resulting from electricity and fuel consumption. The total cost of PLA production from cassava starch to PLA resin (scenario 2) is 2.82 USD/kg PLA, which is higher than the total cost of PLA resin production from cassava root in the first scenario (i.e., 2.71 USD/kg PLA). The differences in the results of the two scenarios result from the fact that the production of PLA from cassava root in scenario 1 produces two by-products during starch extraction: cassava flour and gypsum. The costs and the benefits of these by-products are only included in the first scenario.

Kwan et al. (2018) carry out a techno-economic analysis of a food waste valorisation process for lactic acid, lactide and poly(lactic acid) production. In this study, a techno-economic assessment was carried out to investigate the technical feasibility, profitability and extent of investment risk between lactic acid (LA), lactide and PLA production using food waste powder as the raw material in a plant. The economic performance of the three scenarios was assessed by estimating capital costs, operating costs, and revenue generation. The total capital costs include the fixed investment costs and the operating capital costs. The fixed investment refers to the expenditure for the construction of the plant, including the cost of equipment purchase, installation, piping and other related costs. Estimated operating costs include total variable production costs, fixed costs, plant overheads and general costs. Revenue was generated from the sale of products and from the food waste treatment service fee. Various profitability indicators were employed to evaluate the economic performance of the three scenarios. Kwan et al. 2018 conclude that all scenarios examined in this study are economically feasible, which is demonstrated with a range of economic indicators, with LA production (Scenario I) being the most profitable option. The minimum selling prices for one tonne of LA, lactide and PLA are USD 943, USD 2073 and USD 3330, respectively.

Sanaei and Stuart (2018) investigate the costs and economic performance of producing PLA using an innovative feedstock named triticale. Triticale (X Triticosecale Wittmack) is a crop that according to the authors has the potential to become a preferred industrial energy crop for bio-refineries. Compared to existing cereal crops such as wheat, the plant grows on marginal land and generates higher yields. Another advantage is that this crop

does not compete with food crops. The aim of their paper is to identify an economically promising strategy for the production of PLA based on this new raw material. In addition to several economic indicators to evaluate the economic performance of different production scenarios, the study also provides cost estimates. The baseline scenario features the lowest technological risk while maximising the production capacity of the product. The alternative scenarios involve higher technological risks compared to the baseline scenario but can potentially lead to a better return on investment. The total production costs include the costs of raw materials (biomass and chemicals), energy and operating materials, maintenance and repair, labour, operating materials, insurance and overhead, administration, distribution and sales. The total costs estimated in this study range from USD 911/t PLA to USD 1496/t PLA, with the benchmark scenario having the highest costs.

Manandhar and Shah (2020) investigate the techno-economic feasibility of producing 100,000 tonnes of lactic acid per year from corn grains in a bio-refinery. In doing so, the study estimates the resource requirements (equipment, raw materials, energy and labour) and costs of producing lactic acid from bacteria, fungi and yeast-based fermentation pathways. The study found that lactic acid production costs are very sensitive to sugar to lactic acid conversion rates, corn prices, plant size, annual operating hours and potential use of gypsum. The minimum selling price for the lactic acid produced from corn grain using different fermentation pathways was comparable to the market price of lactic acid. It was found that fermentation pathways using microorganisms such as yeast, which tolerate low pH and have high lactic acid yields, had the lowest production costs, estimated at USD 844/t of lactic acid. The total production costs of lactic acid from corn grain for the bacteria and fungi-based fermentation pathways were USD 1181/t and USD 1251/t, respectively. The authors point out that improvements in process efficiency and lower costs for raw materials, equipment and chemicals could further reduce production costs and improve the techno-economic feasibility of lactic acid production.

Table 1: Comparison of literature results

Study	Feedstock(s)	System boundaries	Annual production capacity (in tonnes)	Range of results: Costs per tonne PLA (USD)	
				Min.	Max.
Chiarakorn et al. (2014)	Cassava	Feedstock - PLA polymerization	100000	2410	2620
Jim Lunt & Associates (2010)*	Potato; Wood	Feedstock - PLA polymerization	50000	1808	2977
Kwan et al. (2018)	Food waste	Feedstock - PLA polymerization	10624	3558	3558
Manandhar and Shah (2020)**	Corn grain	Feedstock - Fermentation	100000	844	1251
Sanaei and Stuart (2014)	Triticale	Feedstock - PLA polymerization	100000	911	1496

* converted by us from USD / lb to USD / tonne; ** costs per tonne lactic acid

Table 1 compares the various results of the studies presented and gives the maximum and minimum production costs for a tonne of PLA or, in the case of Manandhar and Shah (2020), for a tonne of lactic acid in USD. The values show a wide range and range

from 844 to 3558 USD per tonne of PLA/LA. The main cost drivers identified in the studies were: costs for raw materials, energy costs, labour costs and capital costs.

The wide range of results is due to the different process routes that were analysed. The processes differ in the selection of feedstocks and in the assumptions made regarding the production process. Therefore, the results are not directly comparable. A significant difference is due to the choice of feedstock, which has a great influence on the results. The choice of feedstock not only affects the costs directly associated with the raw material input, but also changes the subsequent technical steps in the process chain.

Another very cost-relevant factor in PLA production, is the energy use (i.e., electricity, heat) incurred for the individual process steps, particularly in the PLA refinery process. When innovative raw materials are used, the technology, which is not yet fully developed, is usually associated with high energy intensity and thus represents a cost driver. The costs for additives and waste disposal also depend on the choice of feedstock and the subsequent technological process steps.

4 | Uncertainty analysis of cost drivers

4.1 | Methodology

4.1.1 | Production scenarios

In our analysis, we consider the scenario of an integrated PLA production facility, which includes all steps in the chemical conversion of the biological feedstock from pre-treatment to polymerization. This corresponds to the real production structure at large suppliers such as NatureWorks. Specifically, we compare two product systems that differ in the choice of feedstock. The first product system (henceforth termed corn grain-based system) considers corn grain as feedstock substrate and hence reflects the current commercial situation. The process steps can be described as follows: the harvested grains are dried and transported to a corn wet milling facility nearby. There, they are separated by a wet milling process into their components, including starch. The starch undergoes enzymatic hydrolysis, splitting starch polymers into glucose monomers. Then, the glucose solution enters a bacteria-based fermentation process taking place in a facility integrated in the same refinery site. Calcium hydroxide is added to the solution to maintain the pH-value, the resulting calcium lactide is then acidified by means of sulfuric acid, generating lactic acid. The lactic acid is purified and then undergoes a polymerization process, also located at the same refinery site. After a series of pre-treatment steps, ring-

opening polymerization is performed to obtain PLA molecules, which are purified by means of chloroform and methanol.

The second product system (henceforth termed corn stover-based system) assumes corn stover to be the feedstock substrate. This has consequences for the chemical conversion processes, as in this case lignocellulose instead of starch represents the chemical feedstock. Harvested stover is pre-treated through a washing and grinding procedure. Then, the resulting fine stover particles undergo an acid hydrolysis to obtain a fermentable sugar mix as an input to the fermentation procedure. Once lactic acid is obtained, the final steps are identical to those observed for the corn grain-based system. Figure 1 depicts the process structure of the two systems. Regarding the geography of production, we assume in both systems that the PLA facility is located in the US. There are two main reasons for this. Firstly, it reflects the current production situation for corn-based PLA production on the part of the global supplier NatureWorks. Secondly, a large part of the input prices required for the cost analysis is only available on a USD basis and reflects the US cost situation.

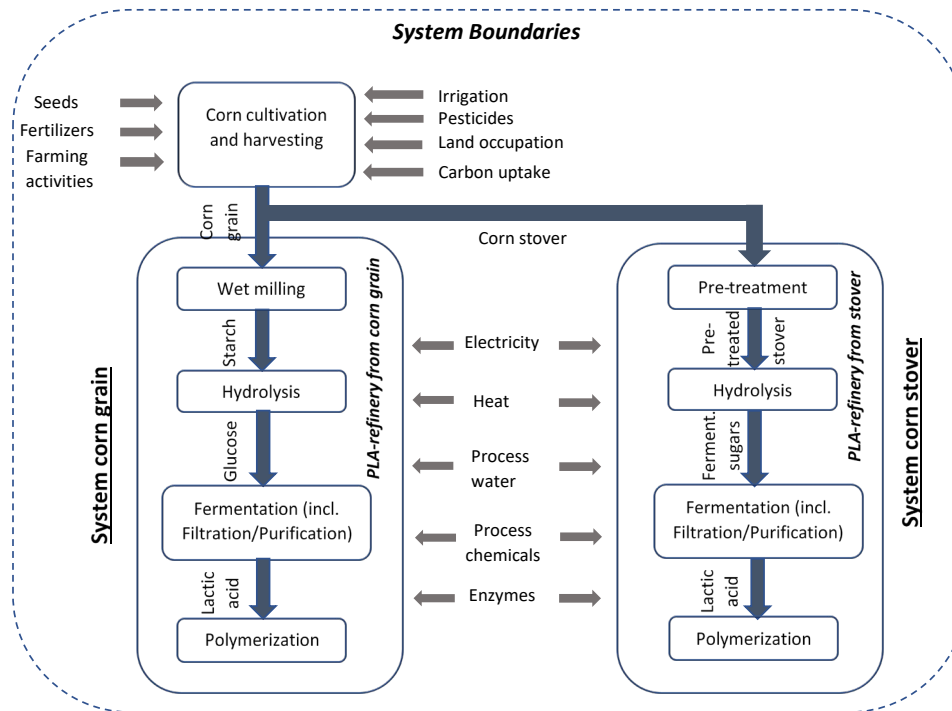


Figure 2: Description of the two product systems considered (Source: own representation)

4.1.2 | Monte Carlo technique

Due to the absence of detailed sector-wide data on the input mix, there exists considerable uncertainty regarding the cost structure of bio-based plastics and PLA in particular. IFBB (2020) offers some average indicators, but only for the processing line of feedstocks itself, not for the use of energy and auxiliary materials. When reviewing current research, there is considerable heterogeneity in the technical data underlying the life cycle assessments in the literature, due to different data origins (experiments, process simulations, real-life production samples) and specific technological setups. This not just concerns alternative process routes for different feedstocks, but also the input mix involved in PLA production based on one and the same feedstock. Table 2 depicts for four important inputs the range of input use intensities in the production of corn-grain-/ corn-stover-based lactic acid found in recent papers in the literature.

Table 2: Range of input intensities for producing one kg of lactic acid reported in recent literature

Production based on corn grain					
Input	Unit	Milling and hydrolysis		Fermentation	
		Min.	Max.	Min.	Max.
Corn grain	kg	1.507	2.390	-	-
Electricity	kWh	0.002	0.002	0.002	0.312
Heat	MJ	1.906	2.192	12.161	18.700
Lime	kg	-	-	0.372	1.759

Production based on corn stover					
Input	Unit	Pre-treatment and hydrolysis		Fermentation	
		Min.	Max.	Min.	Max.
Corn stover	kg	1.734	2.107	-	-
Electricity	kWh	0.070	0.080	0.009	2.388
Heat	MJ	2.379	2.737	6.882	19.870
Lime	kg	-	-	0.976	1.015

Sources: Adom & Dunn (2017); Harbec (2010); Maga et al. (2019); Ögmundarson et al. (2020); Vink et al. (2015)

Cost uncertainty is not limited to technical parameters. Variations in input prices are another issue, both in a spatial (regional markets) and a time dimension (volatility). An essential task for a meta-analysis of PLA production costs is thus to make the extent of input-specific variations transparent. Then, implications for overall cost uncertainty can be assessed. In the following, we apply Monte Carlo simulation as a common tool for such a task. It has been used for cost estimations by various studies (Ge & Asgarpool, 2011; Wang et al., 2012), including the cost structure of corn-based biofuel production (Petter & Tyner, 2014), but has to the best of our knowledge not yet been applied to PLA production. The basic idea behind the Monte Carlo approach is to capture the output uncertainty of a system by means of specifying probability distributions for the relevant input parameters. Conducting a very large number of draws from these distributions and computing for each draw the resulting output leads to a distribution of output values, in our case a distribution of the unit costs of PLA production.

A first step is to identify the most relevant cost drivers, whose variations are supposed to be reflected by statistical distributions in the model. Based on our discussion of literature results, four major cost items stand out within the variables costs of corn-grain based PLA production: feedstock use, electricity consumption, heat consumption and use of lime in the fermentation stage. For these items, variations in input requirements as well as in prices are reflected by stochastic modelling. In addition, uncertainty in the size of capital costs is accounted for as well.

A second step is to make adequate distributional assumptions for the relevant cost inputs. The PERT distribution and the Triangular distribution are popular distribution families in Monte Carlo risk assessment, mostly because they feature easy-to-interpret maximum and minimum values as distribution parameters (Petter & Tyner, 2014). However, ideally the choice of a probability distribution should not be theoretically imposed but rooted in empirical observation. In many applications, this is prevented by the small number of data points available for a parameter value. In our case, this primarily holds for the technical input indicators. Following the meta-analysis approach, we draw for this on the input values reported by the life cycle studies cited above. The few observed values show a tendency to cluster around the mean, with single outliers in both directions. On this basis, we prefer the PERT distribution over the Triangular distribution, as the former assigns less probability to the tails. For the price indicators, a larger amount of information in the form of price time series is available (see next section). In this case, the existence of market price volatility does not justify the specification of clear upper and lower bounds for the price distributions. Instead, we specify a lognormal approximation as an approximation for the input prices.

Then, based on the distributional assumptions made, parameter values for each item-specific distribution are determined as sample estimates from the available data. Regarding capital costs, we are reliant on the estimates provided by the relevant cost analysis papers. As discussed above, they differ in basic assumptions on depreciation rates, maintenance costs and alternative returns to capital. We consider capital cost uncertainty by applying PERT distributions for each of these three parameters, specifying as minimum and maximum values the respective extreme values among the available estimates. The remainder of cost items (further variable cost components and labor costs) are considered in the form of fixed quantities and prices.

Concerning the corn stover-based system, the same methodological approach as for corn grain is followed. An examination of the existing data reveals that the same factors (feedstock, heat, electricity, lime) are dominating the cost performance and are therefore modelled as stochastic distributions here as well. In doing so, a specific issue represents the quantification of a feedstock price. Unlike corn grain, corn stover is not traded in a standardized manner on commodity market platforms. Hence, there exists no market price data that can be utilized as a transparent cost source. Fortunately, there is a comprehensive research literature that aims to assess the costs of corn stover as a production input through alternative means. The general approach is to divide these costs in two categories: costs related to the harvesting of the stover from the field and opportunity costs of alternative usage. Measured harvesting costs comprise activities like shredding, baling, storing and (sometimes) transport. The opportunity costs can only be measured in an indirect way, by considering the specific benefits of leaving the stover on the field. These benefits are typically monetized by estimating their nutrient contributions to the soil and

calculating the expenditures for mineral fertilizers needed to compensate the nutrient loss from harvesting. We follow this approach by drawing on data from this literature. The procedure of data collection is sketched in the next section.

4.2 | Data sources

Following the methodological approach outlined above, the data requirements consist of three types of information: technical input quantities, unit prices of variable cost components and fixed cost estimates. Estimates for input quantities are drawn from recent papers on life cycle assessment, complemented by additional information on feedstock quantities from IFBB market reports. Only these sources offer information on input use in the necessary degree of detailedness required for our meta-analysis. Data on input prices are obtained from a variety of public sources. To reflect the scenario of US-based PLA production, price information at the national US level was generally favored. For three of the four major variable cost items high-frequency US price data were available: corn grain, heat and electricity. For all these items, parameters of the current price distribution were estimated based on a subsample of values from the last five years. For the fourth major item (lime), prices were only available for the period from 2017 onwards. Accordingly, the period 2017-2020 represented here the calculation basis. Prices for the less relevant variable cost components were retrieved from different market platforms. In those cases where time series data was available, five-year averages were calculated to cancel out short-term volatility. Data on relevant parameters (total investments, depreciation rates, maintenance rates, return on capital) stems from the cost analysis papers cited above. All sources for particular items are listed in the Appendix.

Specific input requirements for corn stover-based PLA production can be drawn from the recent analyses by Adom & Dunn (2017) and Ögmundarson et al. (2020). Even though both sources consider the same process routes, they differ quite substantially in the use of certain inputs, pointing to a still high degree of technological uncertainty. We address the implications of this uncertainty by considering the input data from these papers as extreme ends for the probability distributions of our input values. Concerning the capital costs of corn stover-based production, no detailed results are yet available from the cost analysis literature. The only available source represents Liu et al. (2015). We adopt their estimate for total investment expenditures and apply to this the capital cost parameters of the corn grain-based system, in order to minimize distortions for the system comparison.

5 | Results

5.1 | Deterministic case

As a first perspective, a deterministic case is considered. For each production input, prices and quantities are estimated as the mean values obtained from the data sources listed in the Appendix. The resulting cost estimates can be interpreted as a reflection of the Status Quo observed for production technologies and input markets according to the available sources of information. In Table 3, estimates for the variable unit costs and their components are presented for both product systems. The first important result is that variable unit costs of corn stover-based PLA production are already now estimated to be at a similar level as corn grain-based PLA production. At the same time, the cost composition differs in parts sizeably between the two systems. This starts with the feedstock stage, due to the price differences between the two feedstocks on a per kg basis. While the underlying average price of corn is 0.138 USD / kg, stover use is estimated to come at a cost of only 0.052 USD / kg. Concerning the latter estimate, harvesting costs are the dominant source (0.034 USD / kg stover). The opportunity costs of additional fertilizer use only make a minor contribution (0.018 USD / kg stover). This cost advantage in the initial stage is however compensated by significantly higher process costs for the corn-stover based system in both pre-treatment and fermentation. This, in turn, is partly a consequence of a more energy-intensive processing. More specifically, electricity requirements in fermentation are more pronounced in the corn stover-based system, something in which the two existing literature sources that conduct such a feedstock comparison coincide (Ögmundarson et al., 2020; Adom & Dunn, 2017). Another reason is the use of the costly enzyme cellulase in the pre-treatment of corn stover, contributing alone 0.04 USD to the cost per kg PLA.

Table 3: Variable unit costs in system comparison

	USD/kg PLA	
	System corn grain	System corn stover
<i>by production stage</i>		
Feedstock	\$0.27	\$0.10
Pre-treatment	\$0.01	\$0.08
Fermentation	\$0.38	\$0.50
Polymerization	\$0.08	\$0.08
Total	\$0.74	\$0.76
<i>by cost type</i>		
Material use	\$0.66	\$0.61
Energy use	\$0.08	\$0.15

Source: own calculations

Concerning the results for capital costs (see Table 4), the fact that only one source was available to quantify this cost segment for the corn-stover based system represents an important limitation to the representativeness. Nevertheless, it is noteworthy that estimates for capital unit costs based on this source significantly exceed the range of capital unit cost estimates derived from assumptions of the corn grain literature. In sum, this implies a gap in our deterministic analysis of about 20 Cents / kg regarding the total unit costs.

Table 4: Fixed and total unit costs in system comparison

<i>by component</i>	USD/kg PLA	
	System corn grain	System corn stover
Labor costs	\$0.05	\$0.05
Maintenance & repair	\$0.11	\$0.17
Depreciation	\$0.12	\$0.16
Return on investment	\$0.16	\$0.24
Fixed unit costs	\$0.44	\$0.62
Variable unit costs	\$0.74	\$0.76
Total	\$1.17	\$1.38

Source: own calculations

In view of the partly large fluctuations between the input data used, however, these results conceal a large part of the underlying uncertainty. This applies to both the technological dimension and the input prices. Given the differences in the input mix, this potentially affects the corn grain-based and corn stover-based systems to different degrees. This is examined in more detail in the Monte Carlo simulations in the next section.

5.2 | Stochastic case

Table 5 presents statistics summarising the results of the Monte Carlo simulations for corn grain-based PLA production. Comparing the production steps, the fermentation costs show the highest level of uncertainty, followed by the feedstock corn grain costs. The variations in fermentation costs are to some extent due to observable differences in the estimated energy intensities, especially with regard to the extent of heat utilisation, between the available studies. Variations in the level of nutrient costs (Kwan et al., 2019) are also relevant here. Variations in feedstock costs are less a consequence of volatile corn prices, but more due to discrepancies in estimated input quantities between

sources. Uncertainty in capital costs concerns both the annual loss in value of the capital employed and the level of annual expenditures for maintenance.

Table 5: Distribution of unit costs for corn grain-based PLA production

System corn grain	USD/kg PLA			
	Mean	Std. Dev.	Max.	Min.
Feedstock	\$0.27	\$0.02	\$0.32	\$0.21
Pre-treatment	\$0.01	\$0.00	\$0.01	\$0.01
Fermentation	\$0.38	\$0.05	\$0.55	\$0.26
Polymerization	\$0.08	\$0.01	\$0.12	\$0.05
Variable unit costs	\$0.74	\$0.05	\$0.91	\$0.57
Fixed unit costs	\$0.44	\$0.03	\$0.51	\$0.36
Total unit costs	\$1.18	\$0.06	\$1.37	\$1.00

Source: own calculations

Table 6 shows the same statistics for the Monte Carlo simulations of the corn-stover based system. In this instance, the range of results from the drawings is somewhat more pronounced. This is primarily due to the greater uncertainty regarding the costs of the pre-treatment stage. Specifically, it is above all the price of the enzyme cellulase, for which strongly fluctuating values can be found in the literature (see also Liu et al., 2016). The likewise quite significant variation in the fermentation costs is more strongly attributable to fluctuations in electricity use than in the corn grain scenario. In the case of feedstock costs, the uncertainty about the extent of harvesting costs is primarily in the foreground. Histograms for variable and total unit costs in both product systems are shown in Figure 3. Overall, large areas of overlap can be observed here.

Table 6: Distribution of unit costs for corn stover-based PLA production

System corn stover	USD/kg PLA			
	Mean	Std. Dev.	Max.	Min.
Feedstock	\$0.10	\$0.02	\$0.15	\$0.06
Pre-treatment	\$0.08	\$0.06	\$0.58	\$0.03
Fermentation	\$0.50	\$0.04	\$0.65	\$0.37
Polymerization	\$0.08	\$0.01	\$0.12	\$0.06
Variable unit costs	\$0.77	\$0.07	\$1.30	\$0.59
Fixed unit costs	\$0.63	\$0.04	\$0.74	\$0.51
Total unit costs	\$1.40	\$0.08	\$1.97	\$1.13

Source: own calculations

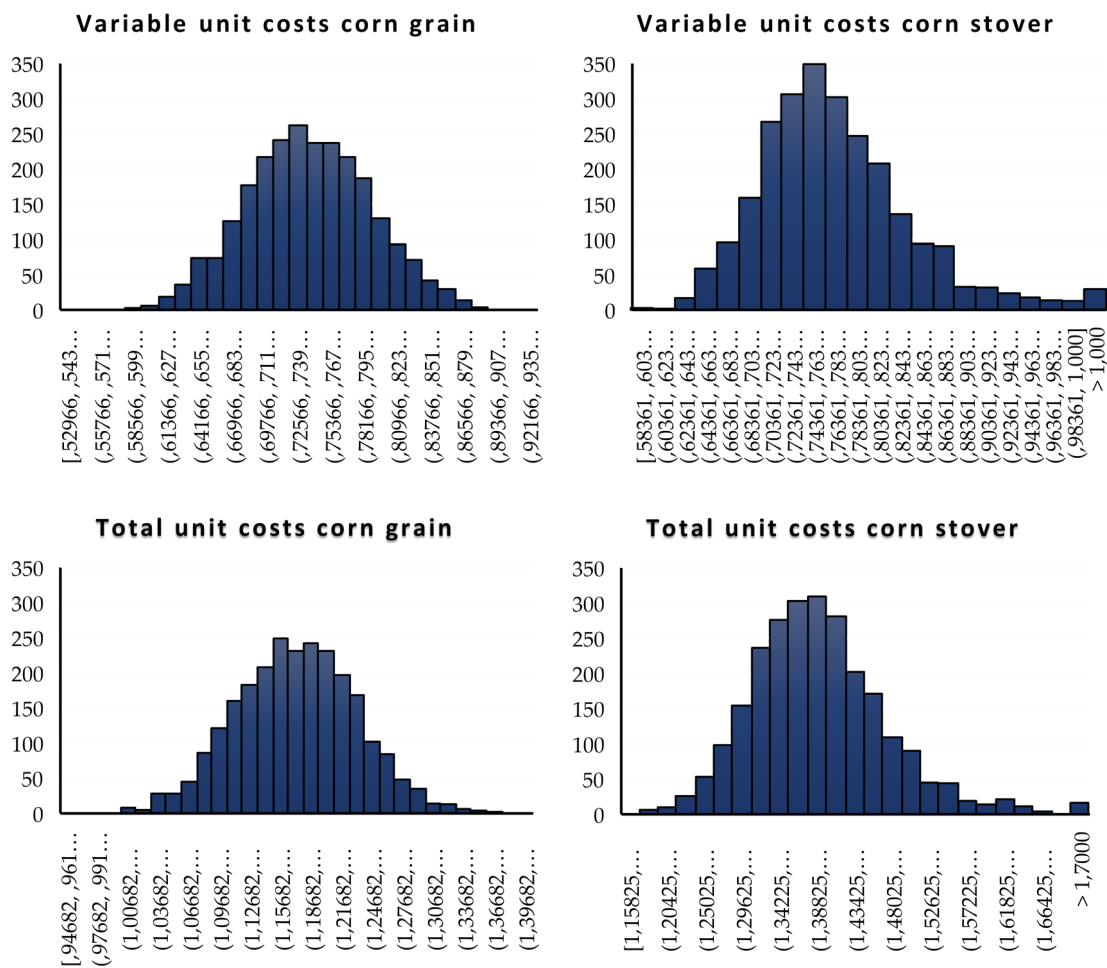


Figure 3: Estimated distributions of variable and total unit costs in both product systems (Source: own calculations)

A comparison of the range of our results to the unit costs reported in the literature can be found in Table 7. The results of our corn grain scenario are roughly in the range of the results reported by Manandhar and Shah (2020). A direct comparison of the corn stover scenario with literature results is difficult, as the studies investigating innovative feedstocks differ considerably in their scenario specifications. In principle, however, the higher degree of maturity of corn stover-based production seems to be reflected in cost advantages compared to third-generation feedstocks such as food waste. However, isolating the role of technology would require a consistent comparative analysis of different innovative feedstocks under the same basic setup.

Table 7: Comparison of own results with the literature

Study	Feedstock(s)	System boundaries	Cost estimates: \$/MT PLA	
			Min.	Max.
Own	Corn grain	Feedstock - PLA polymerization	977	1401
Own	Corn stover	Feedstock - PLA polymerization	1130	1972
Chiarakorn et al. (2014)	Cassava	Feedstock - PLA polymerization	2410	2620
Jim Lunt & Associates (2010)*	Potato; Wood	Feedstock - PLA polymerization	1808	2977
Kwan et al. (2018)	Food waste	Feedstock - PLA polymerization	3558	3558
Manandhar and Shah (2020)**	Corn grain	Feedstock - Fermentation	844	1251
Sanaei and Stuart (2014)	Triticale	Feedstock - PLA polymerization	911	1496

* converted by us from USD / lb to USD / tonne; ** costs per tonne lactic acid

5.3 | Long-term scenarios

The calculations carried out so far were based on data from the recent past and served to present the Status Quo. At present, bio-based materials play only a minor role on the plastics markets, as discussed in section 2. In the future, however, a significant increase in production capacities is expected. The industry association European Bioplastics expects global production capacities to grow by 36 % over the period 2020-2025 (European Bioplastics, 2020). Longer-term estimates forecast global capacity growth of 79 % for the period 2018-2030 (Doehler et al., 2020). An important prerequisite for the realisation of these growth rates is an improvement in the price competitiveness of bio-based polymers like PLA. The future development of the cost structure will play a central role here. Against this background, scenarios for the long-term cost development of both product systems are investigated in this section, with the year 2030 defined as the target year. The basis for these scenarios is, on the one hand, the expected development in input prices. We focus here on three major inputs for which external long-term projections on price development are available: electricity, heat (natural gas) and corn grain. Long-term projections for US industry prices of electricity and natural gas are obtained from EIA (2020). US corn price predictions are obtained from the current USDA long-term projections (USDA, 2020).

On the other hand, potential changes in input intensities are considered as well. Given the aforementioned capacity growth, a likely source for such changes are static and dynamic scale economies in production. Static scale economies arise directly from im-

proved capacity utilization. Fixed costs are spread over a large production quantity, reducing costs of the single unit. Dynamic scale economies are productivity improvements resulting from learning effects of increased production experience. Given the still limited market outreach of bio-based plastics, some potential of unexploited learning effects should remain for the future. The extent of its productivity impact is however highly uncertain. Due to the absence of sector-level production data for bio-based polymers, no statistical evidence regarding productivity increases is available from the research literature. Daugaard et al. (2015) report estimated learning rates for products from the biotechnology sector in total, presenting a wide range of annual rates from 5 % to 20 % productivity improvement. In our projections, we address this uncertainty by comparing different scenarios for this parameter. Since anything bigger than 5 % p.a. leads to implausibly high cost reductions over the 10-year-projection we are studying, we restrict our attention to the following three scenarios: 0 %, 2 % and 5 %.

At the same time, it is unlikely that productivity improvements cause all input requirements to decrease in a homogeneous manner. Depending on the type of adjustments in the production technology, improvements could asymmetrically affect the energy intensity or the use of specific process chemicals. Since it is impossible to predict the exact nature of future technological change, we reflect also on this type of uncertainty by means of alternative sub-scenarios, distinguishing cases where the learning rates either affect the intensity of all energy inputs or of all material inputs. Moreover, simulations have in all cases been undertaken for both product systems. Since our projections involve no assumptions on the evolution of production capacities and no information on the future evolution of investment requirements is available, the simulation exercises are limited to the estimation of variable unit costs.

Table 8 presents the results for all scenarios, together with the results of the current benchmark scenario from section 5.1. When comparing corn grain-based with corn-stover based production, it is evident that the individual scenarios have very different effects on the estimated production costs of the two product systems. In the scenario without productivity improvement, i.e. pure price change, the production costs are initially hardly changed in both cases. Only the costs for process heat make a measurable difference here compared to the benchmark scenario. While the EIA projections for the US industry price of electricity for 2030 imply a slight decrease of -2.6 % compared to the price in the benchmark scenario, the price of natural gas increases by 10.6 %. Corn prices, according to USDA projections, remain almost constant until 2030 (+ 1.4 %). Larger discrepancies arise in the scenarios featuring learning effects.

A general decrease in material intensity reduces costs in all process steps, most strongly in fermentation. In the corn-grain-based system, the overall cost reduction is somewhat greater than in the corn-stover-based system. This is due to the higher share of material consumption in production costs in the corn grain-based system. This difference is only

significant in the scenario with 5 % annual productivity growth. Even in the corn-stover-based system, however, variable unit costs would be halved by 2030 in this scenario. In contrast, the effects of declines in energy intensity in the same magnitude would be much smaller. In this respect, the corn-stover based system benefits more due to its currently higher energy intensity. In the 5 % productivity scenario, the cost advantage is reversed in favor of the corn-stover based system.

In reality, a comparison of the systems is complicated by the fact that, due to the different degrees of maturity, different extents of learning effects can be expected for the two technologies. Ögmundarson et al. (2020) assign a Technology Readiness Level (TRL) of 4-5 to technologies based on second-generation feedstocks, compared to a level of 8-9 for first-generation feedstocks. Moreover, the same authors estimate the optimization potential for corn grain-based PLA as "low", the potential for corn stover-based PLA as "medium". This implies for the latter technology higher potentials for productivity increases via learning effects. Since the exploitation of this potential is associated with an increase in production volumes, this will also have a favorable effect on fixed unit costs in the medium term. In turn, this will additionally reduce the cost disadvantage compared with first-generation technology. However, given the current data situation, the speed at which this process will take place cannot yet be plausibly estimated.

Table 8: Results of long-term projections: variable unit costs

USD/kg PLA				
	Current		Scenario 2030: no technological change	
	<i>System corn grain</i>	<i>System corn stover</i>	<i>System corn grain</i>	<i>System corn stover</i>
<i>by production stage</i>				
Feedstock	\$0.268	\$0.101	\$0.268	\$0.101
Pre-treatment	\$0.009	\$0.076	\$0.011	\$0.079
Fermentation	\$0.380	\$0.501	\$0.400	\$0.514
Polymerization	\$0.080	\$0.080	\$0.080	\$0.080
Total	\$0.737	\$0.758	\$0.759	\$0.774
<i>by cost type</i>				
Material use	\$0.661	\$0.611	\$0.660	\$0.610
Energy use	\$0.076	\$0.147	\$0.099	\$0.164
	Scenario 2030: 2 % p.a. reduction material intensity		Scenario 2030: 2 % p.a. reduction energy intensity	
	<i>System corn grain</i>	<i>System corn stover</i>	<i>System corn grain</i>	<i>System corn stover</i>
<i>by production stage</i>				
Feedstock	\$0.209	\$0.079	\$0.268	\$0.101
Pre-treatment	\$0.011	\$0.065	\$0.009	\$0.075
Fermentation	\$0.331	\$0.433	\$0.381	\$0.482
Polymerization	\$0.063	\$0.063	\$0.080	\$0.080
Total	\$0.615	\$0.640	\$0.738	\$0.738
<i>by cost type</i>				
Material use	\$0.516	\$0.477	\$0.660	\$0.610
Energy use	\$0.099	\$0.164	\$0.077	\$0.128
	Scenario 2030: 5 % p.a. reduction material intensity		Scenario 2030: 5 % p.a. reduction energy intensity	
	<i>System corn grain</i>	<i>System corn stover</i>	<i>System corn grain</i>	<i>System corn stover</i>
<i>by production stage</i>				
Feedstock	\$0.099	\$0.037	\$0.268	\$0.101
Pre-treatment	\$0.011	\$0.040	\$0.005	\$0.068
Fermentation	\$0.203	\$0.281	\$0.346	\$0.424
Polymerization	\$0.031	\$0.031	\$0.079	\$0.079
Total	\$0.344	\$0.390	\$0.697	\$0.671
<i>by cost type</i>				
Material use	\$0.245	\$0.226	\$0.660	\$0.610
Energy use	\$0.099	\$0.164	\$0.037	\$0.061

Source: own calculations

6 | Conclusion

This study investigated cost patterns in the production of the bio-based polymer PLA, comparing two alternative feedstocks: corn grain and corn stover. While PLA production based on corn grain has long been established on a larger scale, the feedstock alternative corn stover, which is interesting from the perspective of land use savings, has not yet reached the stage of mass production. As far as the current cost situation is concerned, we estimate that corn stover-based PLA is already competitive with corn grain-based PLA in terms of variable costs. However, this is overshadowed by the disadvantage of higher fixed costs. In addition, our Monte Carlo simulation clearly demonstrates that cost estimates based on the current state of knowledge are associated with a high degree of uncertainty. This holds particularly in the case of corn stover, foremost with regard to input intensity. At the same time, the identified differences in the cost structure of corn grain- and corn stover-based PLA production imply different responses of cost levels to exogenous developments such as changes in input prices. This makes it difficult to predict the future performance of these two production alternatives.

Finally, our long-term scenarios based on external price forecasts have indicated that the technology factor will continue to be essential for cost competitiveness in the future. A key issue will be the extent to which the two production alternatives can benefit from learning effects in the context of production increases. In this regard, the fact that corn stover-based PLA represents the less mature technology generally implies higher learning potentials. However, the degree to which these potentials can be realized will also depend on the speed at which corresponding production capacities can be built up. In the upscaling phase, capacity growth is likely to be restrained by the demand side. To reach a state of competitiveness, it will hence be important for producers to convince their customers of the environmental superiority of such a feedstock switch. The current public discussion on land usage of the bioeconomy sector can be supportive here. At the same time, one needs to be aware that corn stover is only one of many innovative feedstock options that have proven to be technically feasible. Achieving an optimal balance of cost competitiveness and ecological impacts would require consistent life cycle comparisons between different second- and third-generation feedstock technologies. This represents an important task for future research.

7 | References

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8 | Appendix

Table A 1: Price data used in cost simulations

Items (sorted by step)	Unit	Price (\$) per unit			Source	Time span
		Mean	Mean_log	Std. dev_log		
<i>Feedstock</i>						
Corn grain	kg	0.138	-1.997	0.036	https://quickstats.nass.usda.gov/results/4DBCE9AE-5F84-36AA-BA5A-6936FBD55135	2015-2019
<i>Pre-treatment</i>						
Ammonia, anhydrous	kg	0.450	-0.800	0.060	https://businessanalytiq.com/procurementanalytics/index/ammonia-price-index/	2017-2020
Cellulase	kg	4.197	1.227	0.876	Liu et al. (2016)	-
Chlorine, liquid	kg	0.193	-1.646	0.000	https://www.westlake.com/industry-product-pricing	-
Cyclohexane	kg	0.930	-0.091	0.213	https://businessanalytiq.com/procurementanalytics/index/cyclohexane-price-index/	2017-2020
Electricity	kWh	0.069	-2.680	0.010	EIA US electricity prices for industrial sector	2015-2019
Heat (natural gas)	MJ	0.004	-5.632	0.103	EIA US natural gas prices for industrial customers	2015-2019
Process water	l	0.0001	-9.028	0.000	Kwan et al. (2018)	-
Quicklime	kg	0.122	-2.104	0.014	USGS lime statistics	2017-2018
Sodium chloride	kg	0.212	-1.552	0.041	Statista	2016-2020
Sodium hydroxide	kg	0.110	-2.264	0.382	https://businessanalytiq.com/procurementanalytics/index/caustic-soda-price-index/	2017-2020
Sulfuric acid	kg	0.056	-2.892	0.152	https://businessanalytiq.com/procurementanalytics/index/sulfuric-acid-price-index/	2016-2020

Sulfur dioxide, liquid	kg	0.230	-1.470	0.000	https://www.icis.com/explore/resources/news/2005/12/02/547530/chemical-profile-sulfur-dioxide/	
Urea	kg	0.226	-1.490	0.103	World Bank Commodity 2020	2016-2020
<i>Fermentation</i>						
Electricity	kWh	0.069	-2.680	0.010	EIA US electricity prices for industrial sector	2015-2019
Heat (natural gas)	MJ	0.004	-5.632	0.103	EIA US natural gas prices for industrial customers	2015-2019
Lime, hydrated	kg	0.149	-1.902	0.021	USGS lime statistics	2017-2018
Nutrient cost	-	0.150	-1.897	0.166	Manandhar et.al. (2020)	-
Process water	l	0.0001	-9.028	0.000	Kwan et al. (2018)	-
Sulfuric acid	kg	0.056	-2.892	0.152	https://businessanalytiq.com/procurementanalytics/index/sulfuric-acid-price-index/	2016-2020
<i>Polymerization</i>						
Chloroform	kg	0.368	-1.012	0.178	https://businessanalytiq.com/procurementanalytics/index/chloroform-price-index/	2017-2020
Electricity	kWh	0.069	-2.680	0.010	EIA US electricity prices for industrial sector	2015-2019
Ethyl acetate	kg	0.492			https://www.echemi.com/productsInformation/pd20160820171503533-glacial-acetic-acid.html	-
Heat (natural gas)	MJ	0.004	-5.632	0.103	EIA US natural gas prices for industrial customers	2015-2019
Methanol	kg	0.322	-1.145	0.171	https://businessanalytiq.com/procurementanalytics/index/methanol-usa-price-index/	2017-2020
Stannous octoate	kg	12.000	2.485	0.000	Kwan et.al. (2018)	-
Water, cooling,	l	0.0001	-10.414	0.000	Kwan et al. (2018)	

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