European Commission

JRC TECHNICAL REPORT

Bio-based value chains for chemicals, plastics and pharmaceuticals

A comparison of bio-based and fossil-based value chains

Spekreijse, J.

Vikla, K.

Vis, M.

Boysen-Urban, K.

Philippidis, G.

M'barek, R.

2021

Joint Research Centre

EUR 30653 EN

Contact information
Name: Robert M'barek
Address:
Email: Robert.M'barek@ec.europa.eu
Tel.: +34 954 488 489

EU Science Hub
https://ec.europa.eu/jrc

JRC124141

EUR 30653 EN

PDF ISBN 978-92-76-32459-1 ISSN 1831-9424 doi:10.2760/712499

Luxembourg: Publications Office of the European Union, 2021

How to cite this report: Spekreijse, J., Vikla, K., Vis, M., Boysen-Urban, K., Philippidis, G. and M'barek, R., Bio-based value chains for chemicals, plastics and pharmaceuticals, EUR 30653 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-32459-1, doi:10.2760/712499, JRC124141.

Contents

Acknowledgements

This research was mainly funded through an administrative arrangement between the Directorate General for Research and Innovation (DG RTD) and the Joint Research Centre (JRC). We would like to thank Órlaith Ní Choncubhair and colleagues from DG RTD for their very helpful comments and suggestions.

The authors would like to thank Myrna van Leeuwen, Diti Oudendag, and Heleen Bartelings from Wageningen University and Research Centre (WUR) for fruitful discussions and providing the data from the GTAP database.

The authors are also thankful to Edoardo Baldoni, Claudia Parisi and Tevecia Ronzon from the JRC for comments at an earlier stage of the study.

Authors

Jurjen Spekreijse

Kaisa Vikla

Martijn Vis

Kirsten Boysen-Urban

George Philippidis

Robert M'barek

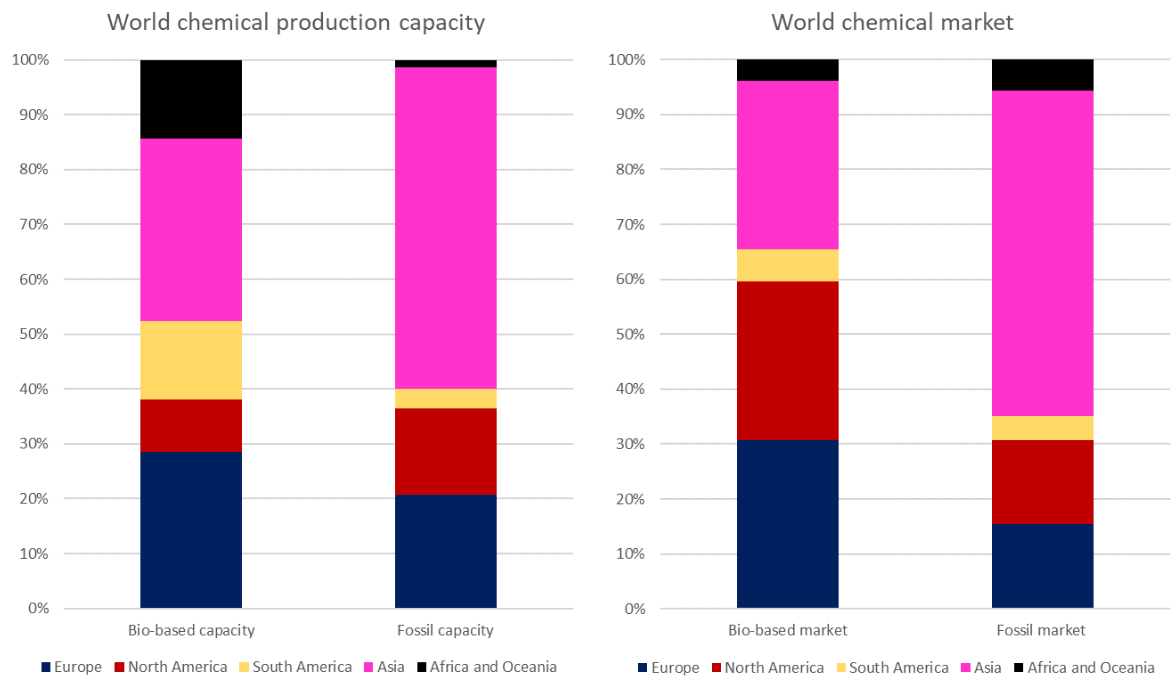
Summary

This report aims to contribute to a better understanding of bio-based chemicals, plastics and pharmaceuticals in comparison to their competing fossil-based technologies, selecting representative value chains for each of the categories. This information is also needed to feed forward-looking modelling tools with aggregated data, which serves as a starting point for simulating different medium- to long-term development pathways for bio-based innovations.

The selection of representative chemicals (organic chemicals that are not polymers) includes the three widely produced compounds of succinic acid, acetic acid, and propylene glycol. Polyethylene (PET) and polyurethane (PUR) were chosen to represent the bio-based plastics sector. Finally, levulinic acid and lactic acid were selected to represent bio-based pharmaceuticals.

The bio-based production cost shares of the representative chemicals, plastics and pharmaceuticals sectors were compared to those for fossil-based production of chemicals, plastics and pharmaceuticals. Overall, the cost shares for bio-based and fossil production show comparable trends. The cost shares show little dependency on the sector (chemicals, plastics, or pharmaceuticals), the main conversion process (fermentation or thermochemical), or the region of production (Asia, Europe, North and South America). On the other hand, the type of feedstock used (sugar or starch, vegetable oil, or woody biomass) does have an impact and is the main difference between the cost shares for fossil-based and bio-based production, with the use of vegetable oil resulting in higher cost shares for feedstock use. This could be explained by the fact that vegetable oil is generally the most expensive of the bio-based feedstocks investigated.

As well as the cost shares, the market share and production capacity of each of the three sectors in the main regions of the world were estimated. These estimates are not based on the representative selection, but a combination of publicly available data sources. See chapter 3, 4, and 5 for the detailed breakdown of the numbers used and their respective references. The following figures, thus, represent the total markets for chemicals and plastics.



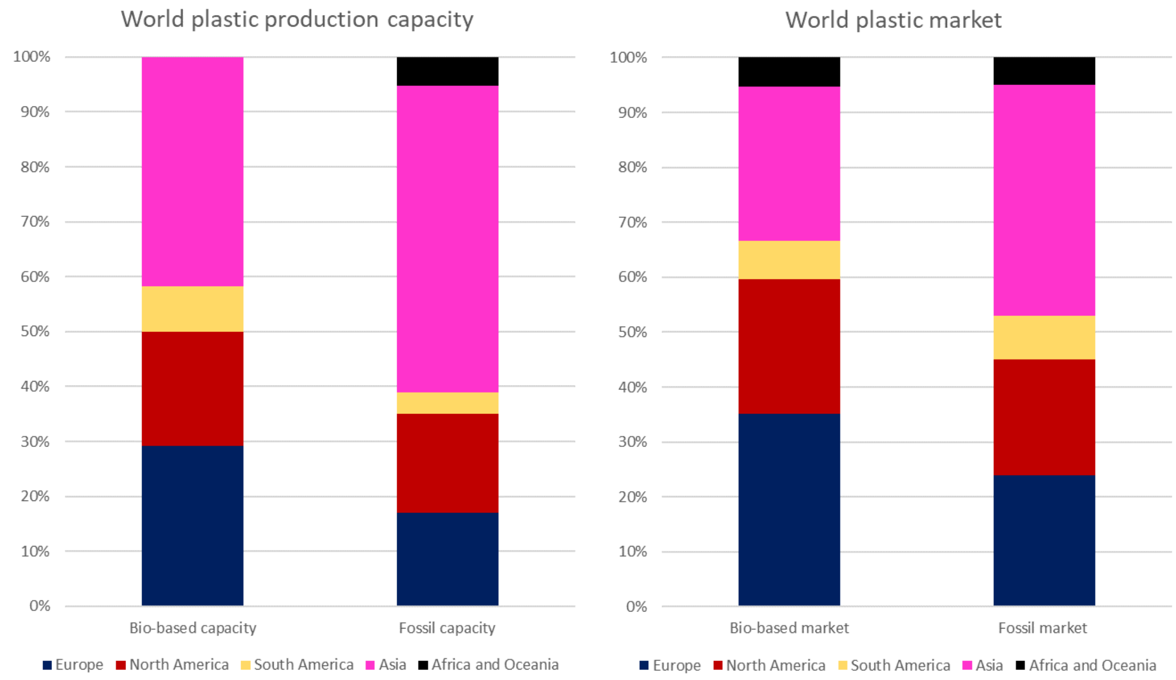
Estimate of the share for the production (based on ktonnes/year) and markets (€m/y) of fossil and bio-based chemicals.

Source: Author's elaboration.

The largest share of global fossil-based chemical production takes place in Asia (58%). This number is much higher than the share of Europe (29%). By contrast, when accounting for total bio-based chemicals however, Europe is much closer to the production share of Asia, with a share of 29% compared to 33% for Asia. Another noteworthy observation is South America, where the share in bio-based production (14%) is much larger than the share in fossil-based production (3%).

The same trend can be observed for the market, with Europe's bio-based chemical market at 31% compared with its fossil-based chemical market at 16%. Like the trend in production, the Asian fossil-based chemical market share (59%) is much larger

than their share in the bio-based market (30%). The South American market is of a similar size (4% of fossil production, 6% of bio-based production).



Estimate of the share for the production (based on ktonnes/year) and markets (€m/y) of fossil and bio-based plastics.

Source: Author's elaboration.

Bio-based plastics show a very similar trend compared to bio-based chemicals. In this sector, Europe plays a greater role in bio-based production (30%) than in fossil-based production (17%). The same holds true for the European bio-based market (36%) compared to the European fossil-based market (24%). Whilst both North and South American figures for production and market size do not show significant differences, the Asian market and production numbers do show significant differences. Here, the share in bio-based production (42%) is significantly lower than the share in fossil-based production (57%), and the share of the bio-based plastic market (30%) is lower than the fossil-based market (43%).

For the pharmaceutical industry, the data quality is of a lower level, which makes it more challenging to reach any firm conclusions. The differences seem to be much smaller than the differences for chemicals and plastics, within 5 percentage points.

The overall trend of the three sectors is that the European share of bio-based global production and the global market is more dominant than its share of fossil-based global production and global market. The opposite holds true for the Asian region, where the share in bio-based production and markets is smaller than their fossil-based equivalents. The exception is the pharmaceutical sector, where no significant differences were observed.

1 Introduction

The products of the chemical industry play an important role in our daily lives. It is estimated that 96% of all manufactured goods require inputs from the chemical industry. Moreover, with 1.14 million employees and sales of €507 billion in 2016, the European chemical industry is one of the largest industrial sectors in the European Union and a leading source of direct and indirect employment in many regions. However, the chemical industry in its entirety is also characterised as a highly energy intensive activity, constituting a large source of greenhouse gas emissions.

Bio-based alternatives, substituting conventional fossil technologies, offer potential solutions for decarbonising chemical activities and additional environmental benefits. Thus, the channelling of biomass into chemical applications is a potentially lucrative outlet for sustaining growth and employment prospects for product diversification within biorefineries and for the contemporary bioeconomy as a whole.

The 2018 update of the Bioeconomy Strategy aims to accelerate the deployment of a sustainable European bioeconomy so as to maximise its contribution towards the 2030 Agenda and its Sustainable Development Goals (SDGs), as well as the Paris Agreement. Within the European Green Deal, in particular the Circular Economy Action Plan underlines the potential of renewable bio-based materials, also in the context of bio-based plastics, as long as it results in genuine environmental benefits, going beyond reduction in using fossil resources.

This report summarises the key results of an analysis of bio-based chemicals, plastics and pharmaceuticals compared to fossil-based technologies for the selected representative value chains for each of the categories.

Chemicals form a large sector and, strictly speaking, any compound could be called a chemical. In this study only bio-based chemicals that fall within the definition of intermediary products were considered for inclusion in this study. An intermediary bio-based product refers to a pure chemical or polymer that is partly or wholly produced from biomass. This is a pure compound that will generally require further processing before it reaches the application stage. In the further processing stage, the intermediary bio-based product is often blended with other, bio-based or fossil-based, chemicals or polymers.

This blending stage is referred to as the blending industry. In the blending industry (semi-finished) products are made, which are usually transported to other industries for applications. As an example, a pure polymer is an intermediary bio-based product. The polymer is combined or 'blended' with stabilisers and other additives to make a plastic in granular form. The plastic granulate is the semi-finished product, which is then shipped to, for example, the toy industry that shapes the plastic into several types of toys. The toy industry is an example of an 'end user/industry' that is not considered in this study.

To differentiate 'chemicals' from the other categories in this study, namely plastics and pharmaceuticals, only organic chemicals that are not polymers and are not mainly used in the pharmaceutical sector were selected.

This report presents the methodology of the choice of value chains (chapter 2) and describes the comparison of fossil and bio-based production and markets for chemicals (chapter 3), plastics (chapter 4) and pharmaceuticals (chapter 5), respectively. Chapter 6 provides some information on the cost shares at industry level. Chapter 7 concludes the report.

2 Methodology and selection of value chains

This chapter first introduces the methodology and selection of value chains, followed by the description of how the relevant data is obtained to derive market and cost information.

2.1 Selection criteria for value chains

It should be noted that intermediary bio-based products are identified, i.e., only the pure components before the blending activities are considered. To differentiate 'chemicals' from the other categories in this study, namely plastics and pharmaceuticals, only organic chemicals that are not polymers and are not mainly used in the pharmaceutical sector were selected.

The selection is based on several criteria:

1. The bio-based value chain is relevant in the EU. A bio-based value chain is relevant if either a significant fraction of its production takes place in the EU, or it has a significant market in the EU. This implies that significant production should be taking place currently. Chemicals without a high current Technology Readiness Level (TRL) that show promise for future developments are excluded from this study.
2. The bio-based value chain is representative of the sector. With a limited selection of value chains, the total selection will not be able to cover a large portion of the sector. However, the selected bio-based value chains should be representative of the chemicals, polymers, and pharmaceuticals sectors. This representativeness should be achieved by aiming to cover the different feedstocks (sugar/starch, oil, wood and waste) and categories of value chains (fermentation, thermochemical and biorefinery).
3. The value chains should have adequate data availability. To minimise the number of assumptions and increase the quality of the data, the selection of bio-based value chains is weighted towards value chains that are expected to have good quality data available.

Three chemicals, two plastics, and two pharmaceutical products were selected. The selection was optimised to get a good representation of each of the sectors, as well as ensuring high data availability. A complete overview of the selected and excluded representatives for the value chains with matched selection criteria can be found in Table 1. The authors estimated data availability based on Spekreijse et al. (2019) and initial screening of the data. The data availability is indicated by an uncertainty indicator, where a 1 indicates very reliable data available and 4 indicates the least reliable data, which requires the author's own estimates (Spekreijse et al. 2019). The current selection of chemicals includes three widely produced bio-based chemicals that give a clear representation of the chemicals sector. The selected compounds (succinic acid, acetic acid, propylene glycol) are important chemicals for the chemical industry. They have multiple applications, such as monomers for plastics, as solvents, in resins applications, as anti-freeze agents, as preservatives to name a few and therefore fulfil the selection criteria. Moreover, the compounds are produced from different feedstocks (sugar/starch, wood, and waste) with various technologies that widen the part of the bio-based industry to be covered in this study. The "B-list" options are 1,4-butanediol, furfuryl alcohol, and itaconic acid, which also have a reasonable production rate in the EU, with 30 ktonnes/year, 40 ktonnes/year, and 10 ktonnes/year, respectively. However, these compounds do not fulfil the selection criteria completely, and were excluded from the selection.

Two candidates were chosen to represent the bio-based plastics sector. Bio-based plastics are mainly produced using fermentation from sugar-based crops and, therefore, polyethylene terephthalate (PET) is a good choice to represent the market. Additionally, PET has a large part in the European market volume of bio-based plastics. To ensure that the selection also covered oil-based crops, polyurethane (PUR) was chosen. However, in the case of PUR, the authors anticipated that the availability of data might prove to be a challenge. In the "B-list", polylactic acid (PLA) has a significant production in the EU. However, with the inclusion of lactic acid as pharmaceutical and PLA being produced from sugar/starch as well, PET and PUR took precedence. Polyhydroxyalkanoate (PHA) has low production numbers, but it has gained sufficient interest. There is also some production in the EU, but recent developments are not promising enough to justify including PHA in the study.

Finally, the third industry is bio-based pharmaceuticals. Levulinic acid and lactic acid were selected to represent this sector. They both have sufficient production in the EU area, and they are produced from sugar/starch. Furthermore, they are produced with different technologies, namely fermentation and thermochemical conversion, respectively. Lactic acid is an interesting case, since it is also used as a feedstock for PLA. The inclusion of lactic acid gives more information on the interconnections between the different sectors. Xantan and terpenes are both used in pharmaceutical industry; however, the chosen chemicals fulfil the selection criteria fully and are a better choice to represent bio-based pharmaceuticals. The reader should note that many other selections of bio-based products could have been made for the analysis performed in this report, and a limited selection of seven value chains could result in a bias towards effects that are only present in one of the selected value chains. The authors have made significant efforts to ensure a balanced selection of products that are currently available on the market and fulfil all the criteria for this selection. At the same time, the selection shows sufficient overlap in characteristics (such as feedstock and conversion method) to observe trends and similarities.

Table 1. Selected, B-listed and excluded chemicals, plastics and pharmaceuticals with feedstock, technology and selection criteria fulfilled.

Chemicals	Compounds	Production (kton/year)	UI	Feedstock	Technology	Selection criteria 1	2	3
Selected	Succinic acid	23	1	Sugar/starch	Fermentation	+	+	+
	Acetic acid	25	1	Wood	Biorefinery	+	+	+
				Sugar/starch	Fermentation	+	+	+
	Propylene glycol	20	1	Waste (Glycerol)	Thermochemical	+	+	+
'B-list'	1,4-butanediol (BDO)	30	2*	Sugar/starch	Fermentation	+	-	+
	Furfuryl alcohol	40	1	Waste (sugarcane bagasse)	Chemical conversion	+	-	+
	Itaconic acid	10	3*	Sugar/starch	Fermentation	-	+	-
Excluded	FDCA	<<1		n.d.	n.d.	-	-	-
Plastics	**Compounds**	**Production (kton/year)**	**UI**	**Feedstock**	**Technology**	**Selection criteria 1**	**2**	**3**
Selected	PET	0	2	Sugarcane	Ethylene from ethanol (fermentation)	+	+	+
	PUR	39	2	Oil	Thermochemical	+	+	-
'B-list'	PLA	7	1	Sugar/starch	Lactic acid from fermentation	+	+	+
Excluded	PHA	<2	2	Waste	Fermentation	+	-	-
	PBAT	-		Fossil	n.d.	-	-	-
	PBS	-		Fossil	n.d.	-	-	-
Pharmaceuticals	**Compounds**	**Production (kton/year)**	**UI**	**Feedstock**	**Technology**	**Selection criteria 1**	**2**	**3**
Selected	Levulinic acid	10	2*	Sugar (Corn)	Thermochemical	+	+	+
	Lactic acid	65	2	Sugar/starch	Fermentation	+	+	+
'B-list'	Xanthan	44	4	Sugar/starch	Fermentation	+	+	-
Excluded	Terpenes	n.d.		n.d.	n.d.	-	-	-

*UI : Uncertainty indicator for the data. *= Based on initial screening. Selection criteria: 1) The bio-based value chain is relevant in the EU. 2) The bio-based value chain is representative for the sector. 3) The value chains should have a good expectation of data availability. Production = bio-based production in the EU, n.d. = not determined*

Source: Authors' elaboration.

2.2 Data collection for value chain analysis

For each value chain, several production sites all over the world and several applications have been selected. This report includes a graphical representation for each of the selected value chains and included products to show them in a clear and concise manner in section 3. The graphical presentation starts at the factory input gate and ends where the intermediary bio-based product is produced. The values shown in these value chains are all normalised to 1 tonne of produced product. The different production sites and applications are distinguished using colour coding. The specific inputs for each main producer are indicated in the value chains as well.

Based on an initial assessment, this study identifies the main bio-based blending industries covering the main markets of the bio-based value product. For example, three blending industries were identified for lactic acid: (1) lactic acid (in its pure form) and its salts (2) production of PLA, and (3) ethyl lactate. The selection of bio-based blending industries is mainly motivated by market size.

To obtain cost-shares of bio-based products and the blending industry, this study collects cost data from key producers around the world. The approach consists of several steps.

The first step locates the main production sites for each bio-based chemical by deriving the main production sites from statistics and overview studies such as E4Tech 2015 and Jogdand 2015. Up to five production sites, that have the largest capacity, or are relevant for other reasons, such as a wildly differing production process, are then incorporated into value chains.

In a second step, this study determines the percentage cost estimates for labour, capital expenditure, energy use, biomass, and other material inputs following a two-step approach.

Using a bottom-up method we estimate the costs of the different inputs for the production of the (intermediate) bio-based product at a typical facility level. Finally, all inputs were brought together to determine the relative cost shares. If bottom-up collection of direct information for the bio-based production facility failed, we apply top-down sector-specific information, including information on similar fossil production facilities. Other secondary data or expert estimates are considered, if needed.

Data availability differs from one production site to another, and in addition varies for each product and product group. In this study, the mentioned data gaps particularly affect the discussions on pharmaceuticals. To overcome these gaps in the data, this study uses assumptions, which, however, are subject to much greater uncertainty than the publicly available data. Using data from other production sites this study estimates capital expenditure and labour costs if this information is missing for a production site[1].

For the purposes of this report, we collect production, trade and price data for the intermediary bio-based products as well as for the main products of the selected blending industries. Where possible, the capacities and locations of the main production facilities were identified to estimate regional bio-based production capacities. This data was supplemented with literature and excerpts from market reports, to establish the best possible picture of bio-based production.

This report provides an overview of the main trade flows between countries and regions by showing the import and export volumes (in ktonnes) of the top 20 exporting and importing countries, structured by main region, i.e., Europe, North America, Asia, South America, Middle East & Africa and Other countries. The category “other countries” contains all countries that collectively have a smaller trade volume than the top 20 countries. These countries’ exports account for a world market share

1 Capital expenditure is generally difficult to determine. In the process of designing and implementing a new production facility, there are often multiple engineering steps, each decreasing the uncertainty involved with estimating capital expenditure. However, up to the moment where detailed engineering is performed and a precise plan of the production facility is drafted, the capital expenditure still shows very large uncertainties. Detailed engineering of production facilities is a long and laborious exercise and therefore, a rough method was used to estimate the capital expenditure for production sites where project costs were not made public. This study uses this method in about half of the cases. Here, the general ‘rule of 0.6’ was applied (Tribe and Alpine 1986, Sweeting 1997). This rule is a commonly used tool in the field of engineering as a quick method to estimate capital expenditure for a plant, when the capital expenditure for a similar plant with a different size is known. The 0.6 rule is shown in the following equation: $\frac{C_1}{C_2} = (\frac{V_1}{V_2})^{0.6}$

In this equation, C stands for the capital expenditure of two plants, where V stand for the production volume. Other versions, where the value of 0.6 is modified, are known as well. However, these do not add significant certainty to the capital expenditure estimate. Therefore, a single method was applied across the entire study to ensure consistency in the methodology. With the total investment determined, a 15-year linear regression was assumed to determine the yearly CAPEX costs.

Next to the capital expenditure, a similar equation can be used to estimate the workforce. Here, the factor 0.6 is changed to 0.25 and the capital expenditure is exchanged for the required workforce (L) (Sorrels 2017): $\frac{L_1}{L_2} = (\frac{V_1}{V_2})^{0.25}$

of less than 0.25% and their imports for a world market share of less than 1%. Trade data is extracted from Abrams World Trade Wiki (ABRAMS)[2].

This report also compiles price data for the intermediate bio-based products, the main bio-based products of the blending industries, and the fossil equivalent products. Trade data (value and volume) serves as an important source of price information which is supplemented by prices mentioned in the literature.

An indication of the cost disadvantage ratio of bio-based equivalents to fossil-based technologies is provided based on expert opinion and/or secondary data estimates. For each selected bio-based value chain, price data of the main product and products of the main blending industries was collected and compared to the fossil equivalent prices (if available).

2 Abrams World Trade Wiki: https://en.abrams.wiki/tools/marketintelligence?utm_source=partner&utm_medium=website&utm_campaign=uncomtrade. Link is also posted on the website of UN Comtrade Labs (https://comtrade.un.org/labs/). This study uses data provided by Abrams World Trade Wiki, to overcome the problem of missing data for emerging sectors in the UN Comtrade database (https://comtrade.un.org/data). Abrams World Trade Wiki complements UN Comtrade data with estimation procedures to interpolate missing values. In the absence of trade statistics (i.e. product has no distinctive 6 digit HS code) secondary sources are utilized as much as reasonably possible to provide a coherent overall picture at regional level.

3 Comparison of fossil and bio-based chemical production and markets

3.1 Selection of value chains for chemicals

Based on the methodology outline in section 2, this study selects three chemicals, namely succinic acid, acetic acid and propylene glycol.

Succinic acid is an organic acid produced by fermentation of sugars extracted from feedstock such as sugar or starch crops or by crude glycerol. The source of glucose and dextrose depends on the plant location, and it may be cane sugar, corn glucose or corn starch. The fermentation processes require water and yeast, and sometimes additional chemicals to enhance yeast growth or for acidity regulation. Some plants also produce ammonium phosphate $(NH_4)_3PO_4$ as a side-product that can be sold as fertiliser. Succinic acid is an innovative bio-based chemical with multiple production sites in the EU. This makes succinic acid highly relevant for the EU and makes the value chains representative of the chemical sector in the EU. Moreover, succinic acid is relevant for multiple blending industries, where it is used in plasticisers, cosmetics, lubricants, plastics, and pharmaceuticals. Figure 1 shows the value chain of succinic acid.

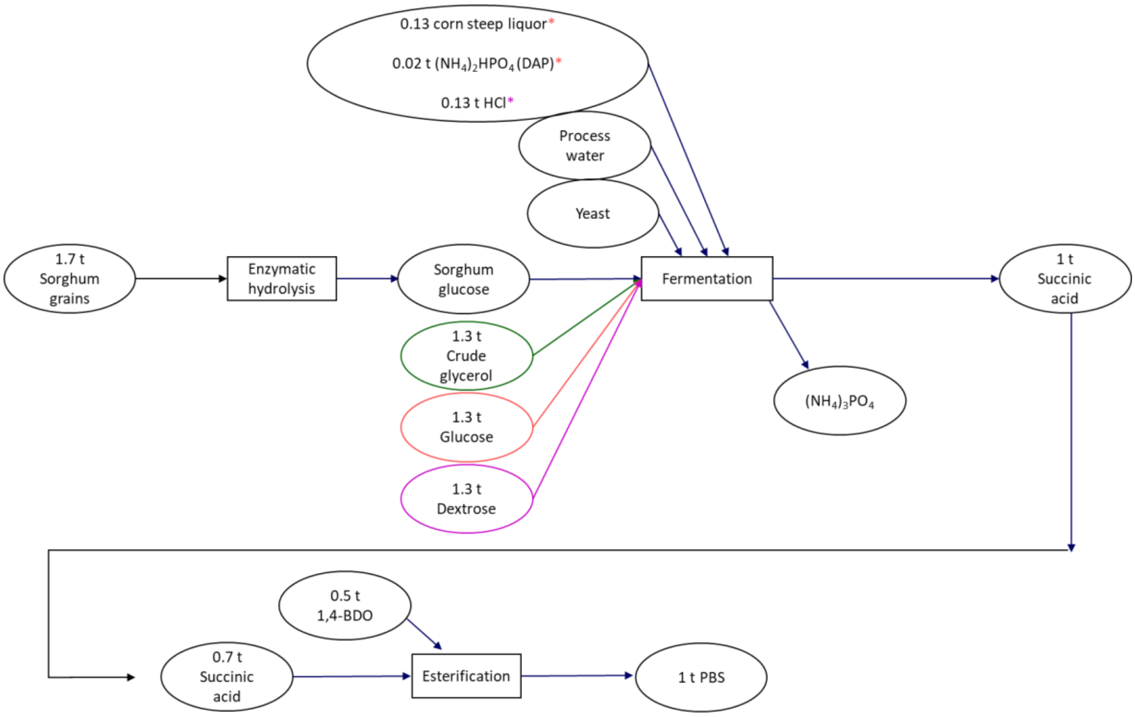


Figure 1: Succinic acid value chain. Note: colours depict different production processes

Source: Authors' elaboration.

Acetic acid is a typical platform chemical, with many end-uses and applications as depicted in Figure 2. Due to its status as a platform chemical, it is a common chemical that is produced and used at many sites throughout the EU. This makes acetic acid a very relevant chemical and a good representative for the chemical industry.

Fossil acetic acid is mainly produced from methanol and carbon monoxide, while bio-based acetic acid can be produced in several ways. These methods often include producing acetic acid as part of an overall product portfolio. Two methods that are commonly used on a large scale are the catalytic oxidation of ethanol, which can be obtained from fermentation and the extraction of acetic acid out of waste streams from pulp and paper mills.

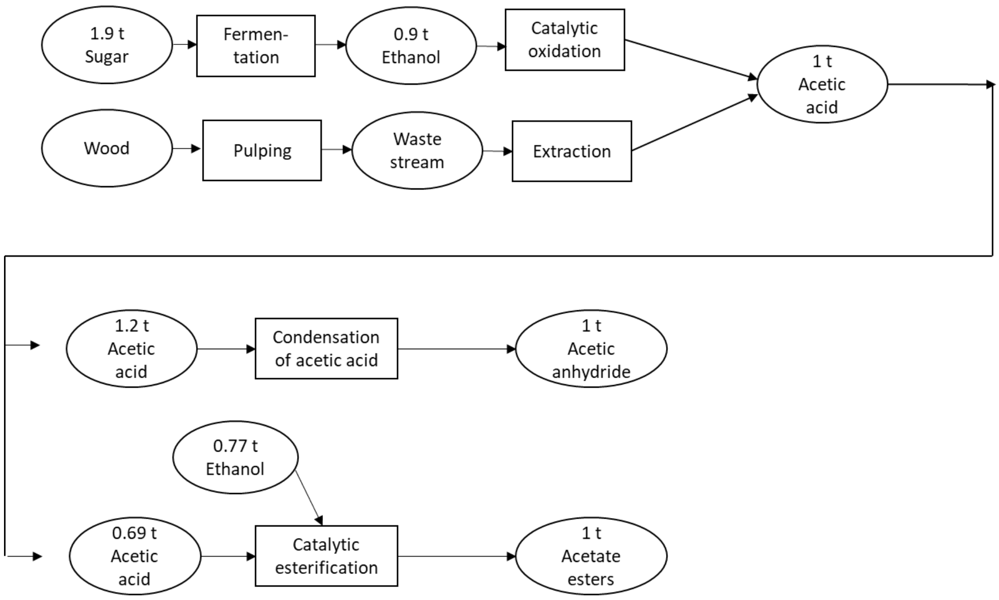


Figure 2: Acetic acid value chain.

Source: Authors' elaboration.

The third value chain representing chemicals is shown in Figure 3. **Propylene glycol** can also be considered a platform chemical with many applications. Alongside applications in food, automotive and cosmetics, nearly 20% of propylene glycol is used in pharmaceuticals (Market Research Future 2019a). It is produced from glycerol, a waste product from transesterification of oils. Another production process converts first starch into sorbitol and the latter then by hydrocracking into propylene glycol and the co-products ethylene glycol and butanediol. As it is produced from a waste stream and at a large scale in the EU, propylene glycol is a good representative value chain of the bio-based chemical industry.

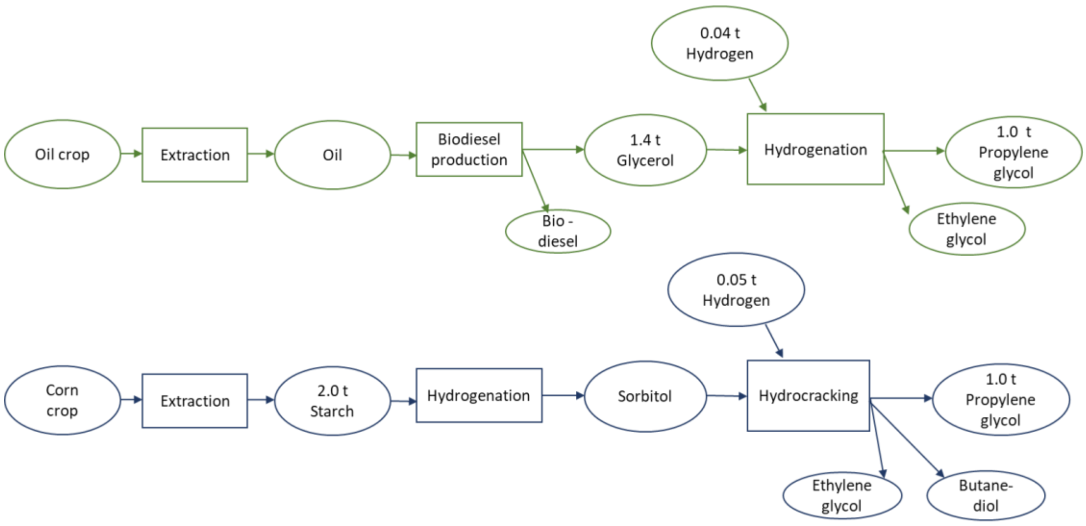


Figure 3: Value chain of bio-based propylene glycol.

Source: Authors' elaboration.

A deeper look at the chemical value chains reveals that succinic acid is a versatile molecule that has several applications. Many sources list its use as a chemical intermediate (e.g., for 1,4-butanediol 1,4-BDO), and in plastics, resins, pharmaceuticals, food & flavourings (Biddy et al. 2016, Hassan et al. 2016 and Nghiem et al. 2017). However, it seems that no company is using it for 1,4-BDO, as bio-based 1,4-BDO can be produced directly from biomass via fermentation (Novamont 2016 and Patel et al. 2018) and is, thus, less costly. For acetic acid, 16.2% of total production is used in fossil blending industries such as vinyl acetate (VAM), acetic anhydride, acetate esters and terephthalic acid (PTA). According to E4tech (2015) about 10% of acetic acid production is bio-based. Most of this bio-based acetic acid is used as vinegar for food, whereas ethyl acetate and acetic anhydride are the most important bio-based blending industries. By contrast, propylene glycol as a typical platform chemical has many well-known applications, hence, the application of the bio-based variant is more difficult to track. Comparing statements of different companies reveals that the most likely applications for bio-based propylene glycol are in Unsaturated Polyester Resin (UPR) and de-icing fluid.

3.2 Fossil-based chemical production capacity and market

The chemical industry is well-documented; however, no single source is available that describes the production or market of each global region of importance. Therefore, a combination of sources was required. First, European production capacity was estimated by Spekreijse et al. (2019) at 87 million tonnes per year (Mtonnes/y). Next, CEFIC has published the turnover of the chemical industry of several important regions (CEFIC 2020a). These numbers in €m were converted to percentages of global turnover. Assuming that the division between regions of the turnover is equal to the division of the production capacity in Mtonnes, a global picture of the global fossil production capacity could be formed. The two data gaps, production in the USA and Brazil, were filled respectively with data from PR Newswire (2019) and Global Business Reports (2018). Overall, this results in a global production of 418 Mtonnes/y of fossil-based chemical production capacity.

Market data is less widely available than production data. The global turnover published by CEFIC (2020a) could directly be used as a number for the global market (€3,347bn in 2019). Using the trade surplus of the EU together with the production, an estimate of the European market could be obtained (€520bn). Next, the published country reports of Italy and France (CEFIC 2020b and 2020c), and public data on Germany from Statista (2019a), gave insight into the structure of the European market. The remaining markets were determined using the trade surplus data from CEFIC (2020a), assuming no change in stock. The data was supplemented by trade surplus data from Brazil, provided by ICIS (2019).

3.3 Bio-based chemical production capacity and market

To estimate the bio-based production capacity, several sources are available. However, the sources do show a wide range in estimates. For example, the total capacity of bio-based chemicals in Europe is estimated at 3.3 Mtonnes/y by Spekreijse et al. (2019) and at 19 Mtonnes/y by BIC (Piotrowski 2018, subtracting plastics and fibre). Another number provided by BIC is that 7.4% of the chemical industry is bio-based (Piotrowski 2018). Using this number results in a bio-based capacity for chemical production in Europe of 6.4 Mtonnes/y. Using the same methodology, the bio-based capacity of the most relevant countries within Europe was determined. For France, the number was updated using data from Ademe (2015). The capacity of the rest of the world was estimated using the ratios presented by Jogdand (2015) and Biopreferred (2018) information was used for the US. This subsection gives an overview about biobased market comparing different data sources in tables 2 and 3.

Table 2. Bio-based chemical market share of main global regions by three sources and the share used in this study.

	Market Research Future 2019a (%)	**Market Research Future 2019b (%)**	**Grand View Research 2019b (%)**	**This study (%)**
Europe	35	34	23	31
Asia-Pacific	21	31	32	
Middle East		4		
Asia				30
North America	29	23	35	29
Latin America		8		
Central and South America			5	
South America				6
Middle East and Africa			5	
Africa and Oceania				4
Rest of the World	15			

Sources: Data taken from Market Research Future 2019a and b, and Grand View Research 2019b.

Table 3. Market size and production capacity estimate of bio-based and fossil chemicals in the most relevant regions.

	Bio-based market (B€)	Fossil market (B€)	Bio-based capacity (Mtonnes/y)	Fossil capacity (Mtonnes/y)
Germany	4.1	187.2	1.7	27.5
Italy	1.1	45.2	0.5	8.1
France	4.3	59.5	0.6	11.6
UK	4.9	-	0.4	5.3
Spain	0.3	-	0.4	6.4
Netherlands	-	-	0.4	7.5
Belgium	-	-	0.4	5.9
Rest of Europe	1.7	228.4	2.0	14.2
Europe total	16.5	520.3	6.4	86.6
US	2.4	464.3	2.3	62.1
Rest of North America	13.1	41.2	0.1	4.0
North America total	15.4	505.5	2.4	66.1
Brazil	3.1	141.1	1.4	12.7
Rest of South America	0.1	6.5	1.7	2.0
South America total	3.2	147.6	3.1	14.7
China	6.7	1217.0	2.7	149.4
Japan	3.6	150.5	-	22.5
Thailand	-	-	0.9	-
South Korea	1.9	-	-	15.8
India	-	-	-	11.1
Rest of Asia	3.8	618.6	3.8	45.8
Asia total	16.0	1986.1	7.4	244.6
Oceania total	1.7	147.6	1.3	2.6
Africa total	0.5	39.8	1.5	3.0
World total	53.2	3347.0	22.2	417.7

Sources: Data taken from several country specific sources as described in section 3.3. Note: "-" indicates that data is not available.

There are many numbers for the global bio-based chemical market. Two market sources list numbers around €10-20bn (€10b, Grand View Research 2019a; €12bn Market Research Future 2019a; €18bn, MarketWatch 2019). It is assumed that these sources are limited to bio-based platform chemicals, due to their lower numbers. Two other sources list numbers in the range of €53bn (€53bn, Market Research Future 2019b, €53bn GlobeNewswire 2019a). This number is more likely to include the entire bio-based chemical market and was used for this study. This number was then divided among the larger continental regions (Europe, North America, South America, Asia, Africa, and Oceania). The division was based on the averaged division presented by three market reports (Market Research Future 2019a, Market Research Future 2019b and Grand View Research 2019b). The comparison of the data from these three market reports and their averaged value used in this study are presented in Table 2.

Dividing the European and Asian markets into the most important countries was done by using the same ratio presented by Inkwood Research (2018a and 2018b). Data for the US is available from Grand View Research (2019b). No data for Brazil was found. It was therefore assumed that Brazil has the same share of the South American bio-based chemical market as the share of the South American fossil-based chemical market. The Australian market was determined using the ratio presented by

Inkwood Research (2018b), where the remaining €452m was assigned to the African market. The overall shares in production and markets are presented in Table 3 and Figure 4.

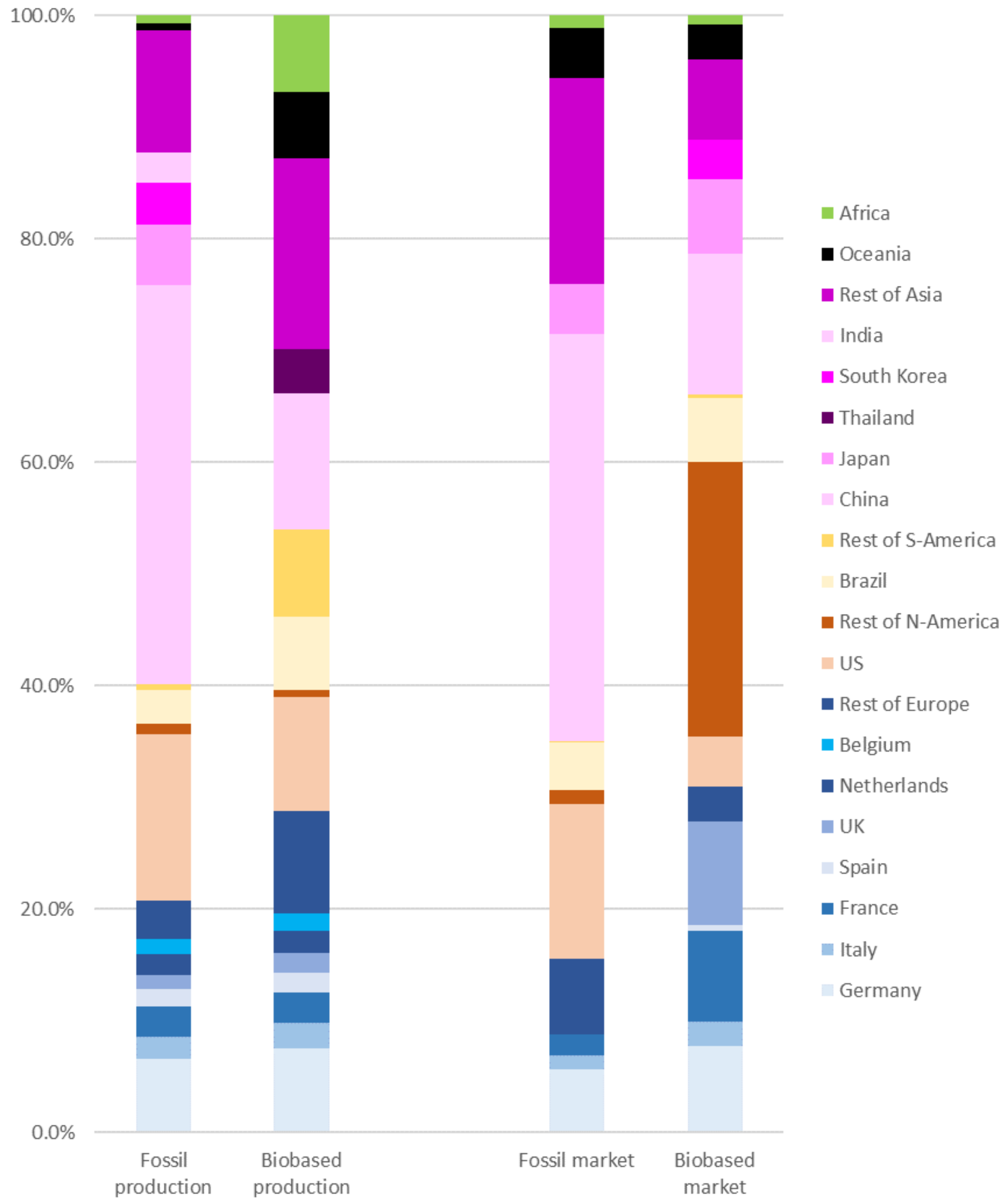


Figure 4. Estimate of the share of important regions for the production (based on ktonnes/year) and markets (€m/y) of fossil and bio-based chemicals.

Source: Authors' elaboration based on table 3.

Figure 4 shows the countries for which data were available. Where data was not available, countries are clustered into larger areas. Due to limited data availability and the combination of data from different sources, using different years and different definitions, care should be taken to draw conclusions only from general trends presented, and not from the exact figures.

Bio-based acetic acid trade is not visible in trade statistics. It is likely that Europe and the USA consume most of their domestically produced bio-based acetic acid and ethyl acetate. The USDA BioPreferred product catalogue[3] indicates that acetic acid is most likely exported from India and Austria to the USA, whilst India is also a probable source of ethyl acetate. The analysis shows that exports for bio-based acetic acid derived products from India to USA and Europe are likely to happen, while at the same time India is a large importer of fossil acetic acid. Based on expert insights, it is surmised that India is strong in ethanol based acetic acid production and is able to sell considerable amounts as bio-based products, while importing cheap fossil acetic acid for own consumption.

Figure 5 shows the share of imports and exports by region for acetic acid and propylene glycol. Europe is the most important exporter of propylene glycol, followed by Asia and North America. The Middle East is a net exporter of propylene glycol as well. Other countries account for an import share of 26% which indicates that propylene glycol is widely used throughout the globe.

Bio-succinic acid is mainly used for PBS (Poly (1,4-butylene succinate)) production, although various applications are possible. Since all PBS producers identified in this study are located in Asia, it is likely that most bio-succinic acid is consumed in Asia.

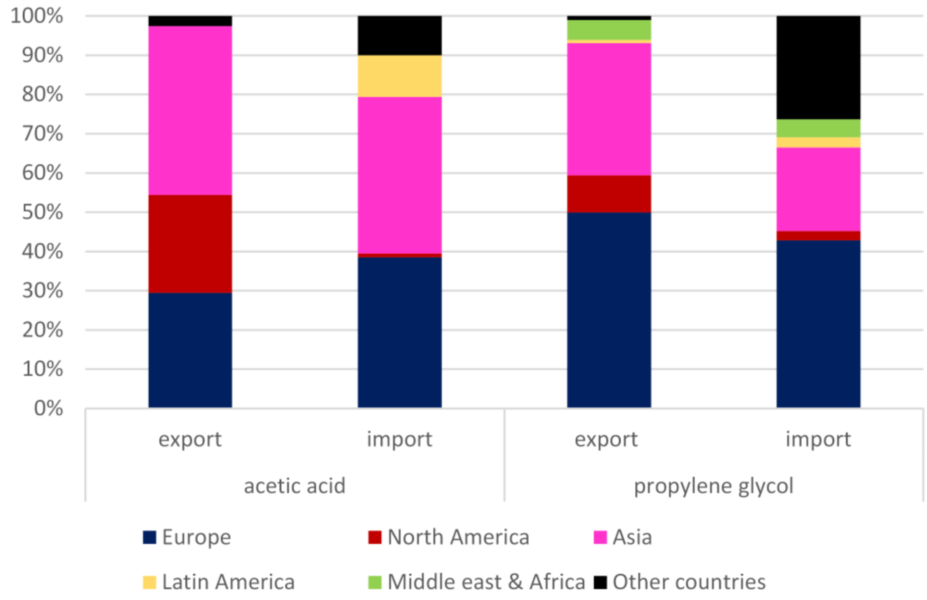


Figure 5. Trade share of acetic acid and propylene glycol by region in 2018. Note: Figure accounts for fossil and bio-based acetic acid and propylene glycol. Furthermore, the totals per continent are the totals of the countries in the top20 of exporters or importers. The other export and import fall under “other countries”.

Source: UN Comtrade data as interpreted by ABRAMS (2020)

[3] https://www.biopreferred.gov/BioPreferred/faces/catalog/Catalog.xhtml

4 Comparison of fossil and bio-based plastics production and markets

4.1 Selection of value chains for plastics

Bio-based plastics get a lot of attention from the public and media. Predictably, this leads to a long list of bio-based plastics available on the market. An overview is given on a yearly basis by European Bioplastics (2018). Most bio-based plastics were also covered in the study Insights into the European market for bio-based chemicals (Spekreijse et al. 2019). For the purpose of this study the following two bio-based plastics have been selected according to the criteria specified in Table 1.

In the group of bio-based plastics, **polyethyleneterephthalate (PET)** has the largest market share. It represents 26.6% of global bio-based plastic production, which makes it a good choice to represent the bio-based plastic sector. Even though there is no significant production of PET in the EU, there is a very significant market for bio-based PET within the EU (214 kilotonnes per year (ktonnes/y), 25% of the global bio-based PET market), which qualifies for a relevant bio-based intermediary product. The value chain of PET is shown in Figure 6.

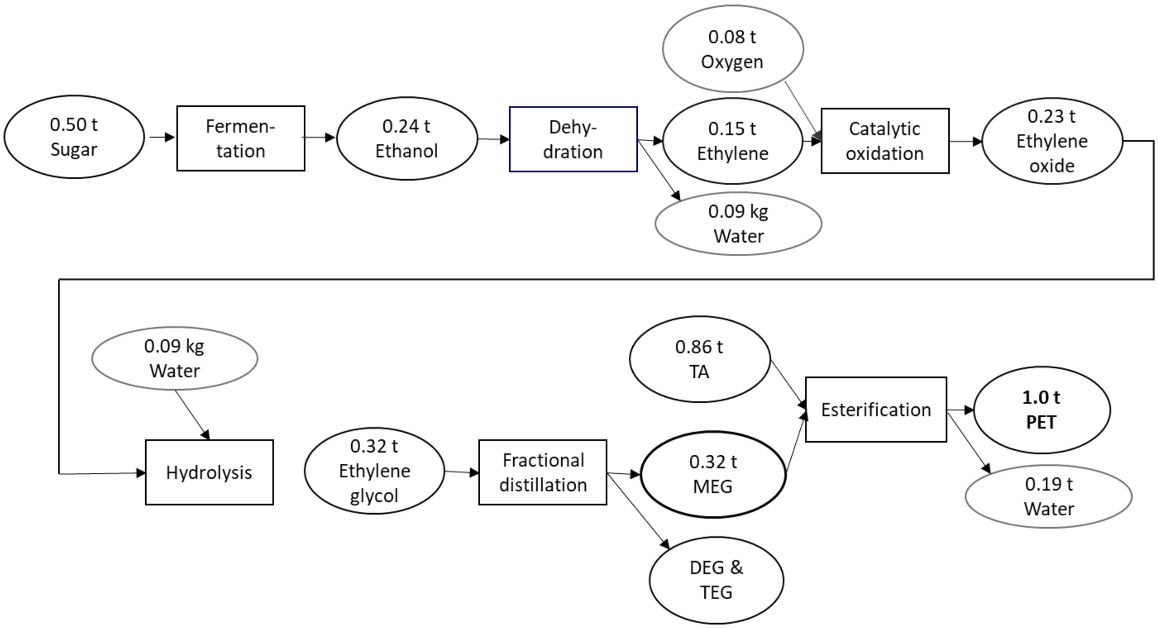


Figure 6. Value chain of bio-PET production.

Source: Authors' elaboration.

PET is made of (bio-based or fossil) mono ethylene glycol (MEG) and terephthalic acid (TA) or dimethyl terephthalate (DMT). TA is the preferred feedstock for process-economic reasons, although DMT may be favoured in polyester film applications due to its adhesion addition quality. The main process steps are raw material preparation, esterification/transesterification, pre-polycondensation and polycondensation resulting in bottle grade PET-chips (ICIS 2010). MEG (mono ethylene glycol) is a form of ethylene glycol. The crude ethylene glycol mixture produced is fed to evaporators to remove water. Fractional distillation under vacuum is used to separate MEG from diethylene glycol (DEG) and triethylene glycol (TEG). Ethylene glycol is produced from hydrolysis of ethylene oxide, which is produced from ethylene, which can be produced from sugar-based ethanol and is thus bio-based. Production of 100% bio-based PET is still in its pilot phase.

Bio-based PET production accounts for 2.4% of total PET production. 87% of total bio-based PET production goes into the production of bottles (2.9% of plastic bottles are bio-based) (Grand view research, 2017; Indorama Ventures, 2019).

Another polymer with a large production volume is **polyurethane (PUR**), whose value chain is depicted in Figure 7. PUR is not included in the report from European bioplastics (2018). However, significant amounts of bio-based PUR are produced, partly in the EU. Even though data availability might be low for PUR, it forms a good addition as it is made from oil crops. Bio-based PUR is made from reacting vegetable oil-derived polyols with isocyanates in the presence of a catalyst or UV-light (Sawpan 2018). As the polyols are already treated chemicals, and isocyanates are chemicals of fossil origin, PUR itself is a blended product. Because of this, we have chosen to consider PUR itself as a blending industry and take epoxidised soybean oil (ESBO) as the bio-based product for this value chain. ESBO is one of the main vegetable oils used for bio-based PUR (Niaounakis 2015) and therefore, this was chosen to represent the bio-based product for PUR production.

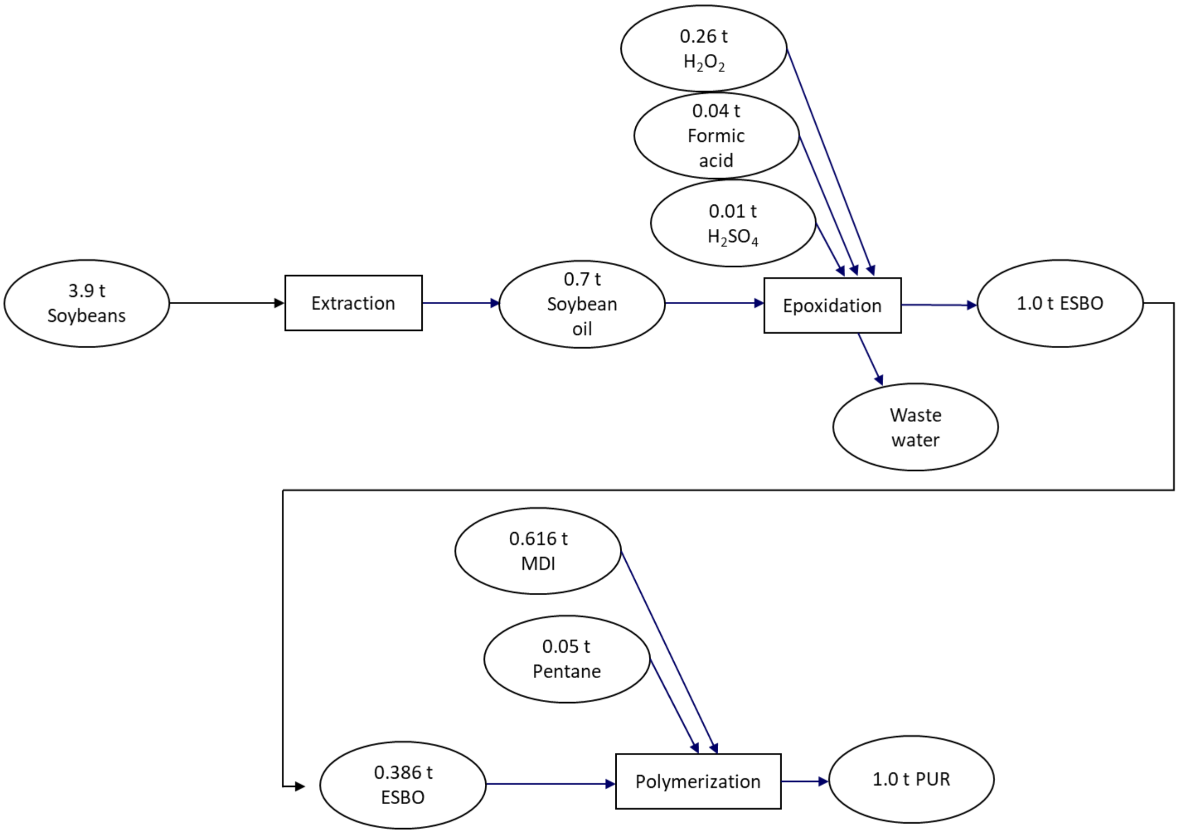


Figure 7. Value chain describing PUR production from soybeans.

Source: Authors' elaboration.

4.2 Fossil-based plastics production capacity and market

The plastic industry is very open on production data, however, there is not a single source that presents all global production in a detailed manner. The global production of 359 Mtonnes/y and a breakdown into several significant regions is presented by Plastics Europe (2019). Further detailed information on European production is challenging to obtain, therefore estimates were required based on data from 2005 (Larotonda 2009). It is assumed that the relative production between the European countries for fossil plastics remains unchanged. This information is supplemented by production numbers from France (5 Mtonnes/y, Ademe 2015) and Germany (18 Mtonnes/y, Beucker 2007). US production (54 Mtonnes/y) and Brazilian production (6.2 Mtonnes/y) were estimated based on data from Statista (2019b and 2019c). Data for Africa, Oceania and India was made available in a publication from the UN (Ryberg 2018), and data for Thailand was obtained from the literature (Marks 2020).

The global demand for plastics in 2019 is estimated at €511bn by Grand View Research (2020a). The division of this demand into the several main markets in the world is given by Ryberg et al. (2018). This data is supplemented by the total demand of the main European markets made available by Plastics Europe (2019). These combined sources give a very complete picture of the main global markets. The only numbers that were added from other sources are the market in the USA (€512bn, Grand View Research 2020a), Brazil (€5.9bn, Plastics Insight 2017, data from 2013) and Thailand (16 B€, Plastic Institute of Thailand 2014).

4.3 Bio-based plastic production capacity and market

There are several conflicting numbers for the global production of bio-based plastics, which can be explained by a variety of definitions and inclusion or exclusion of the more 'traditional' bio-based products. The ifBB (2019) published a number of 2.6 billion tonnes per year (bntonnes/y), where European Bioplastics (2020) estimates the production at 2.1 bntonnes/y. Grand View Research (2016) has a much larger estimate at 5.4 bntonnes/y produced. As a best estimate, the average of the values from ifBB and European Bioplastics were taken, which results in a production capacity of 2.4 bntonnes/y of bioplastics. The breakdown of this number to several key regions is presented by ifBB (2019) and European Bioplastics (2020) (Table 4). However, based on the breakdown per country, the numbers were slightly adjusted to fit the numbers on a country level. The production in Europe

(30% compared with a range of 12% to 25%) and in North America (20% compared with a range of 11% to 18%) were slightly increased and the production in Asia (41% compared with a range of 69% to 45%) was slightly decreased to align the numbers at the country level. It was assumed that no significant production takes place in Africa.

Table 4. Bio-based plastic production capacity of main global regions (in %) by three sources and the share used in this study.

	ifBB 2019 (%)	**European Bioplastics 2020 (%)**	**Fortune Business Insights 2020 (%)**	**This study (%)**
Europe	11.8	25	19	30
North America	10.7	18		20
South America	7.8	12		8.5
Asia	69.4	45		41
Asia Pacific			56	
Oceania	0.3			0.5
Africa				0

Sources: Data from ifBB 2019, European Bioplastics 2020 and Fortune Business Insights 2020

At the country level, production in France was determined to be 195 ktonnes/year (Ademe 2015), the UK at 1 ktonne/year (Cebr 2015), the US at 19% of global production capacity (Golden 2018), Japan at 40 ktonnes/year (Bio-based News 2018) and India at 1 ktonnes/year (Medium 2019). The number found for Thailand (2.4 ktonnes/year, Thailand Board of Investment 2019) did not include the PLA production estimated in this report and was therefore increased by 75 ktonnes/year. No information was obtained for Germany, Italy, Brazil and China. For Italy and Germany, the production was assumed to be relative to their bio-based plastic market. For Brazil, Mordor Intelligence (2017a) estimates the production to be at least 50% of South America, and the Chinese production is estimated to be relative to their share of the Asian production.

There are several estimates for the global bio-based plastic market from 2018, all ranging from €5bn to €6bn. These are €5.8bn (Market Research Future 2019b), €5.3bn (Thailand Board of Investment 2019), €5.4bn (Fortune Business Insight 2020), and €6.3bn (Markets and Markets 2018). This leads to an average of €5.7bn for the global bioplastics market. The North American market is estimated by Fortune Business Insights (2020) at €1.4bn. The markets of Oceania (€57m) and Africa (€229m) were estimated based on their share in the fossil plastic market. The remaining market was divided between Europe, South America and Asia based on the ratio of the market in 2015 (Cebr 2015). The German market is estimated to be 30% of the European market (Mordor Intelligence 2018). Cebr (2015) estimates the Italian market at €370m the UK market at 4 ktonnes/year and the USA market at €560m. The French market is estimated at €313m (Ademe 2015). No information could be found on the Brazilian and Thai market, which were estimated based on their fossil share of the South American and Asian market. According to Mordor Intelligence (2017b), China is 39% of the Asian market, where India contains 3% of the Asian bioplastics market, Nikkei Inc (2019) estimates that 2% of the global market is in Japan.

The overall shares in production and markets are presented in Table 5 and Figure 8, where data from countries is presented where available. When no data was available, countries are clustered in larger areas. Due to limited data availability and the combination of data from different sources, years and definitions, care should be taken to only draw conclusions from the general trends presented and not from the exact numbers.

Table 5. Market size and production capacity estimate for bio-based and fossil plastics in the most relevant regions.

	Bio-based market (€m)	**Fossil market (bn€)**	**Bio-based capacity (ktonnes/year)**	**Fossil capacity (Mtonnes/y)**
Germany	614	30	254	18
Italy	370	17	153	5
France	447	12	195	5
Spain	-	9	-	4
UK	10	9	1	4
Benelux	-	11	-	12
Rest of Europe	606	35	106	12
Europe total	2048	123	709	61
US	560	72	457	54
Rest of North America	817	36	16	10
North America total	1377	107	473	65
Brazil	52	6	100	6
Rest of South America	309	35	100	8
South America total	361	41	201	14
China	638	102	522	108
Japan	114	20	40	14
Thailand	122	16	77	2
India	55	26	1	32
Rest of Asia	712	51	329	43
Asia	1642	215	969	200
Oceania	57	5	12	1
Africa	229	20	0	18
World total	5713	512	2363	359

Sources: Data taken from several country specific sources as described in section 4.3. Note: "-" indicates that data is not available.

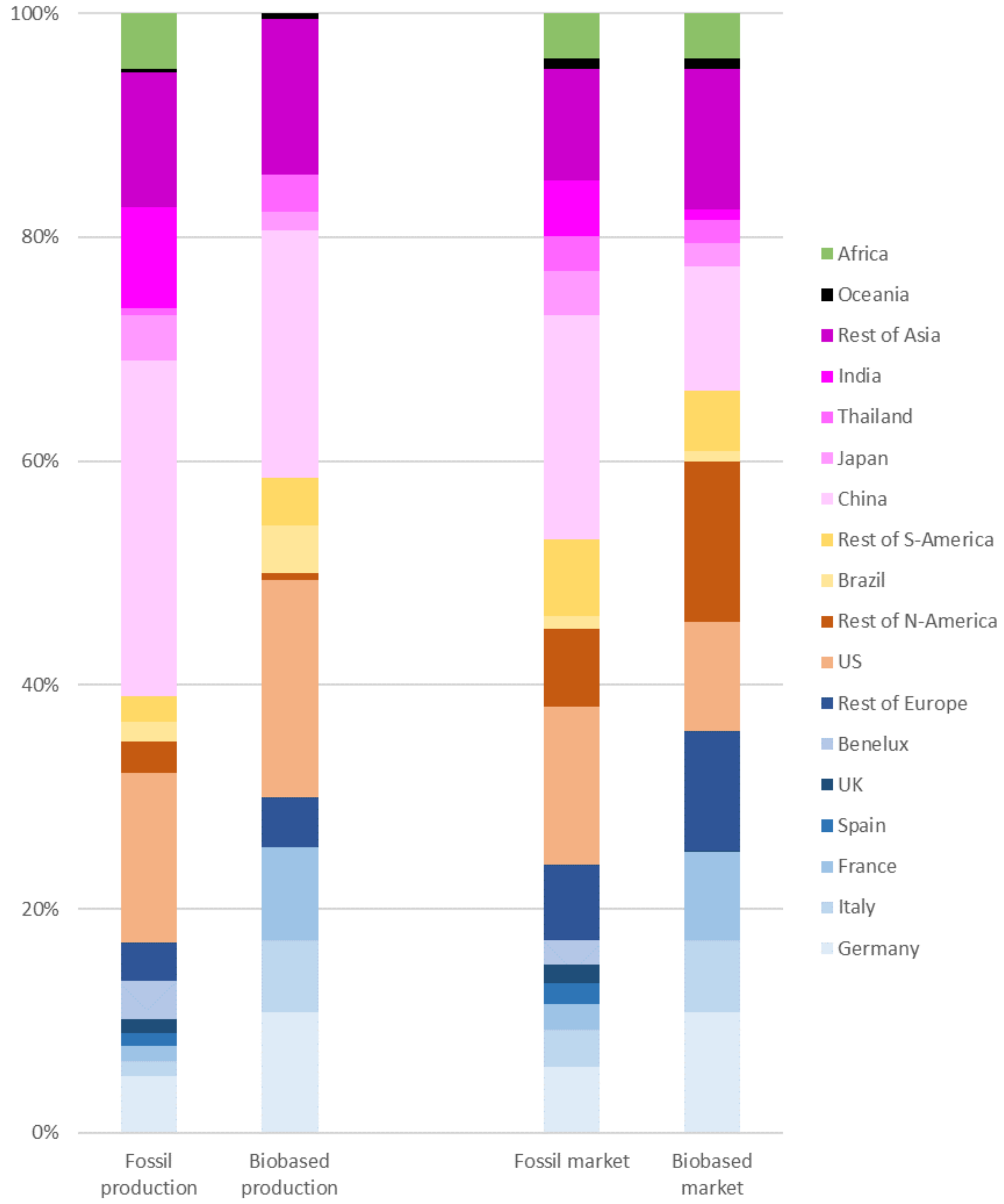


Figure 8. Estimate of the share of important regions for the production (based on ktonnes/year) and markets (based on €m/y) of fossil and bio-based plastics.

Source: Authors' elaboration based on table 6.

Figure 9 depicts the world import and export shares of fossil and bio-based PET in primary forms by region. Asia is the most important exporter of PET (54%). In Europe, exports and imports volumes are in the same order of magnitude. The other regions are net importers of PET in its primary forms. By contrast Europe is the largest exporter of PUR (55%). However, insufficient information was found to determine the production, trade, and consumption of bio-PUR across regions. This may not be surprising given that the total production is estimated to be only 1.6–7.5 ktonnes/year. Given its strong position in the ESBO market, and the origin of the companies found, the USA is likely to be the most active player.

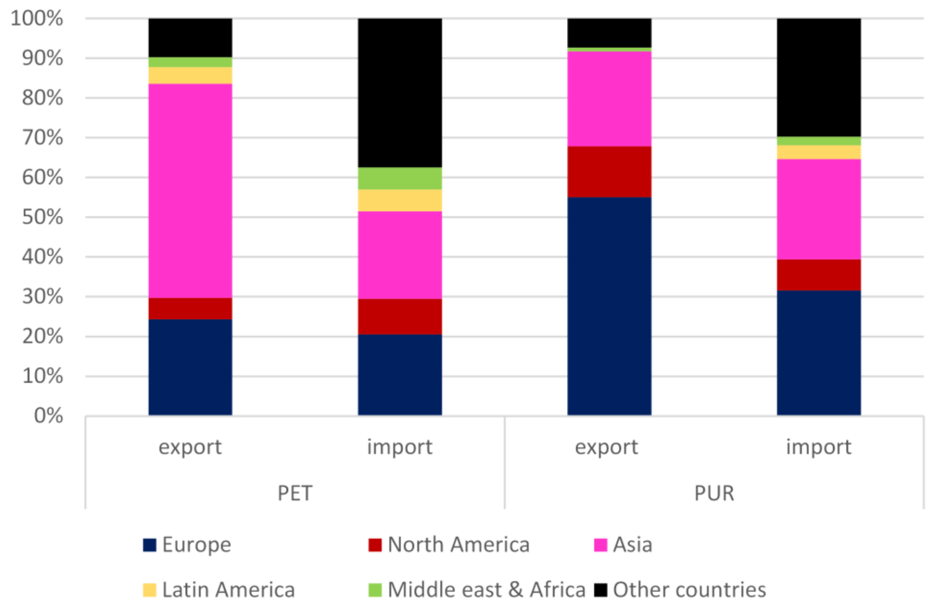


Figure 9: Trade share of PET and PUR by region in 2018. Note: Figure accounts for fossil and bio-based PET and PUR. Furthermore, the totals per continent are the totals of the countries in the top20 of exporters or importers. The other export and import falls under "other countries".

Source: UN Comtrade data as interpreted by ABRAMS (2020).

5 Comparison of fossil and bio-based pharmaceutical production and markets

5.1 Selection of value chains for pharmaceuticals

There are many products that go into pharmaceuticals, and many of these products are bio-based, or 'natural', as they are more commonly known. Pharmaceuticals are a combination of active ingredients with other chemicals such as fillers, binders and sweeteners. To get a good representation of the bio-based pharmaceutical industry, it is important to stay clear of chemicals also used in the food industry. These chemicals have often much broader application as a food ingredient than as a pharmaceutical ingredient. Levulinic acid and lactic acid turned out to be the best representatives for pharmaceuticals according to the criteria in Table 1.

The first product selected is **levulinic acid**, which is a dedicated bio-based chemical, as it has no direct fossil counterpart. Levulinic acid can be obtained from the sugars of biomass waste streams. It has many different applications, which include pharmaceuticals, agricultural use, plasticisers and cosmetics. A significant fraction of levulinic acid (nearly 20%) is produced for the pharmaceutical market and this market is expected to grow significantly (Market Research Future 2019b). The combination of a significant application in pharmaceuticals and a growing market makes bio-based levulinic acid an interesting value chain to represent the bio-based pharmaceutical industry. Figure 10 sketches the value chain of levulinic acid from lignocellulosic material such as paper mill sludge, municipal solid waste, paper and wood wastes and agricultural residues as a feedstock that is converted to levulinic acid in a 2-stage reaction process. The process is acid-catalysed hydrolysis by sulphuric acid (H_2SO_4) in which sugars are first extracted from the biomass and then converted to intermediates following the formation of levulinic acid. The co-products of this process are formic acid and furfural, in addition to ligneous char and acid hydrolysis residues (AHR). The char can be used as a fertiliser or burned along the AHR to fuel boilers on the plant for additional energy. Co-products can be sold for additional income.

Levulinic ketals based on levulinic acid esters are claimed to have a wide range of applications such as non-toxic biodegradable solvents, phthalate-free plasticisers and polyols for polyurethane foams. The solvent and plasticizer products are already being sold on the market (Technon OrbiChem 2016).

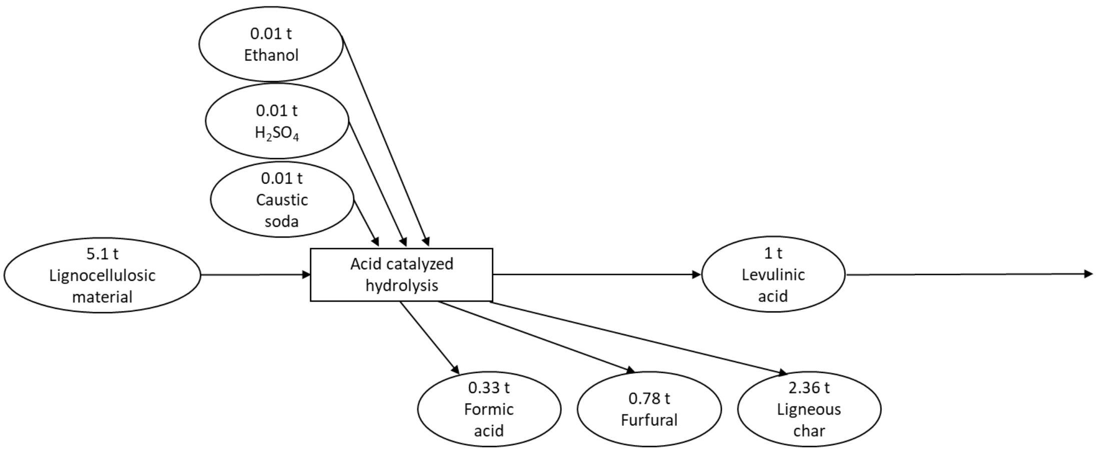


Figure 10. Value chain for production of levulinic acid from lignocellulosic material.

Source: Authors' elaboration.

Lactic acid is considered one of the most well-known organic acids with a wide range of industrial applications. The main applications are found in the production of PLA, ethyl lactate, and potassium lactate. It is an interesting compound for the pharmaceutical industry, as nearly 10% of the produced lactic acid finds its application in pharmaceuticals. Moreover, a large fraction of nearly 40% of lactic acid is used in biodegradable plastics (Transparency Market Research 2019). Therefore, lactic acid serves as an interesting value chain to represent both the pharmaceutical and plastic market. The value chain of lactic is represented in Figure 11 accounting for different production processes and final output (PLA, ethyl lactate and potassium lactate) based on data from representative companies depicted by different colours in the graph. The value chain for lactic acid shows that all production sites use fermentation to produce lactic acid. The key difference is in the source of the glucose, which depends on the location of the plant. This could either be cane sugar, corn glucose, or corn starch. Corn starch is first hydrolysed in an enzymatic process to obtain the free glucose for the fermentation. In addition to lactic acid, a large amount of gypsum is produced. Using different processes (polymerisation, esterification, neutralisation) lactic acid is further processed. This study selects potassium lactate to represent the pharmaceutical use. The four main applications of lactic acid are in the food, chemicals, cosmetics, and pharmaceutical industries as shown in Figure 12.

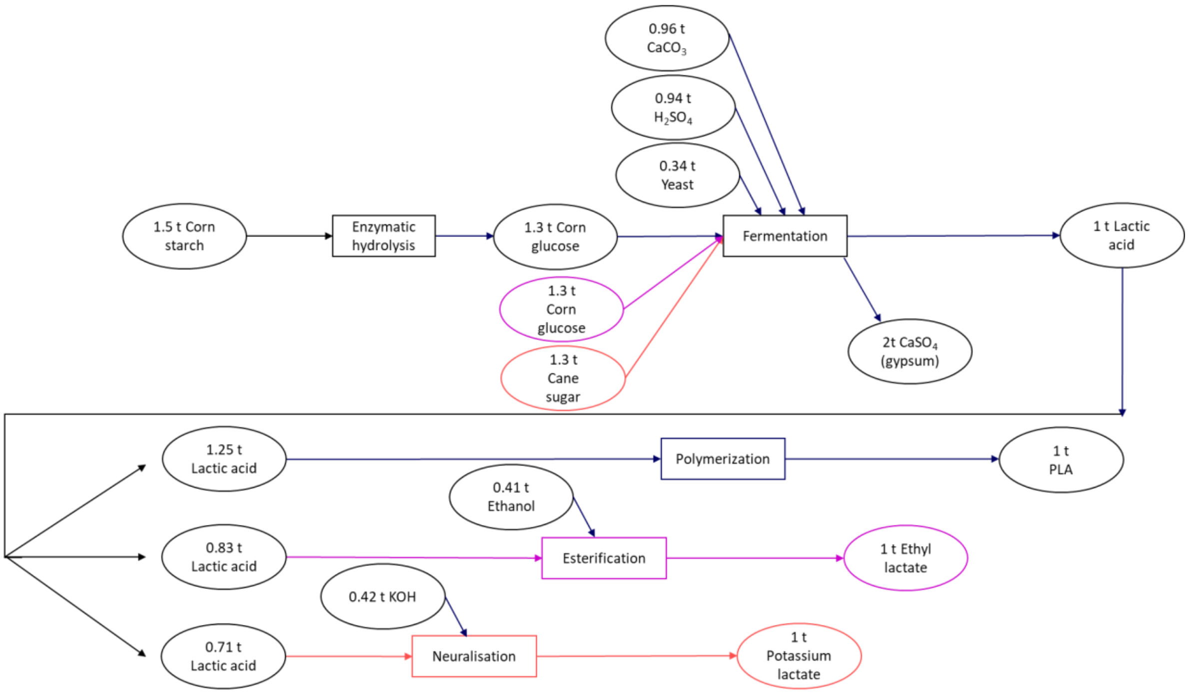


Figure 11. Lactic acid value chain. Note: Colours represent different firms, input use and related processes to produce lactic acid.

Source: Authors' elaboration.

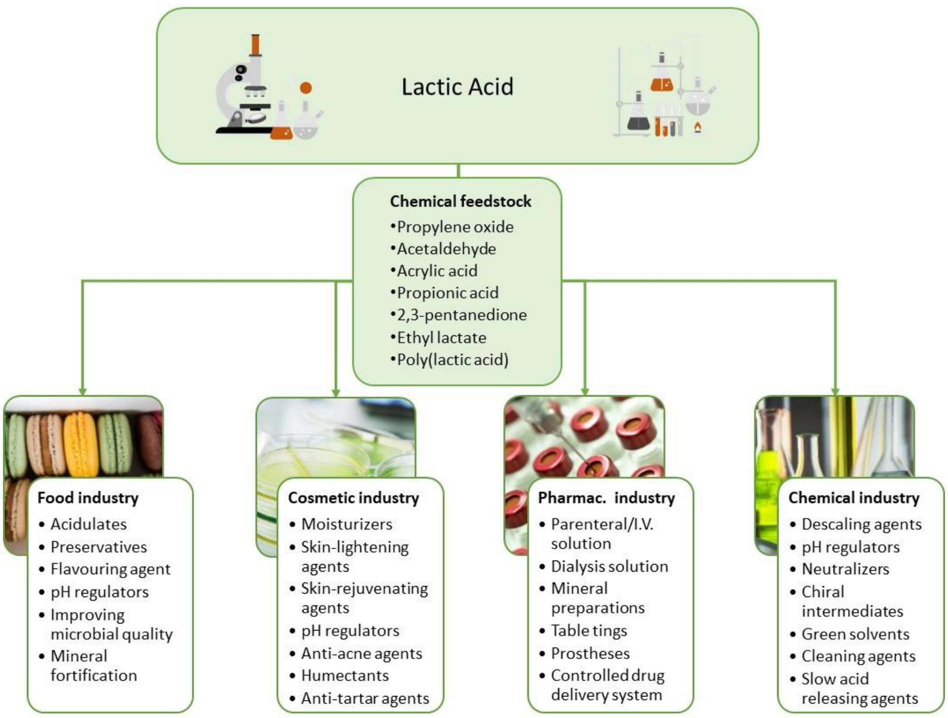


Figure 12. The range of commercial applications of lactic acid and its salt.

Source: Authors' elaboration based on Alsaheb et al. 2015

5.2 Fossil-based pharmaceutical production capacity and market

European market data on the fossil pharmaceutical market is made available by EFPIA, which estimates the European market at €199bn. The European countries with a market greater than €10bn are France (€28bn), Germany (€31bn), Italy (€26bn), Russia (€13bn), Spain (€16bn), and the UK (€21bn) (EFPIA 2018). The Chinese market is estimated at €115bn by China.org (China Daily 2019). Statista (2020) estimates the Brazilian market at €15bn , and the US market at 45% of the global market (€412bn, Statista 2017). The Australian market was estimated at €21bn in 2016 (Drug Development & Delivery 2018), and the African market at €26bn in 2017 (Goldstein Research 2019). Next to this data, a breakdown of the market in several global regions from 2017 was given by EFPIA (2018): North America 48.1%, Latin America 5%, Europe 22.2%, Japan 7.7%, and the rest of the world 17%. Using this data, the remainder of the market shares could be completed. However, to align the data from EFPIA (2018) with the other data obtained, some changes were necessary to prevent China and Japan having a larger market than the total Asian market. Therefore, €10bn was moved from "Rest of Europe" to "Rest of Asia". This can be justified by the fast-growing Chinese market compared to the European and US markets, which plays a role when data from different years is combined.

For the production of fossil-based pharmaceuticals, EFPIA (2018) lists production numbers for each European country (EFPIA 2018). Another important source of data is provided by IFPMA (2017). In this document, all imports and exports of pharmaceuticals in 2014 were listed. Assuming no change in stock, this data can be combined with the exports and imports data by region. With the market, or consumption, known from the previous assessment, an estimate can be made on the production. Only a few sources of more recent data could be obtained, where the production in South Korea and India were estimated at €14bn by Statista (2019d), and the US production was estimated to cover 25% of the global market (€236bn, Market Research Blog 2018). Note that the estimate for total global production reported here shows a slightly different value (€973bn) than the total global market (€916bn). However, by using different data sources from different years, the uncertainty in this study is judged to be within an acceptable margin of error. Note that the production capacities in these sources are all listed in monetary values, rather than production volumes. Therefore, the analysis for pharmaceuticals was performed using a monetary basis (€m) rather than production volumes (ktonnes/year), which deviates from the assessments done for chemicals and plastics.

5.3 Bio-based pharmaceutical production capacity and market

Data sources on the bio-based pharmaceutical industry are very scarce. Therefore, the data presented here is mostly based on sources describing biopharmaceuticals, which often only includes pharmaceuticals produced by biotechnology. Although biopharmaceuticals are generally bio-based, it is not the same definition as bio-based pharmaceuticals and may result in some discrepancies. There are, however, four sources that estimate the global biopharmaceutical industry. These estimates are €214bn (Mordor Intelligence 2019 and IndustryARC 2019), €225bn (BioPlan Associate, Inc 2018), and €242bn (GlobeNewswire 2019b). This results in an average estimate of €224bn. It is estimated that in Europe, 20% of the pharmaceuticals originate from biotech, which results in a European production of €50bn. The distribution of the production within Europe was estimated for 2012 by Ernst and Young (Ernst and Young 2013). The ratio of these numbers was used to estimate the division of the €50bn production in Europe. Other sources indicated that South Korean production is approximately €1.6bn (KHIDI 2018) and Indian production at €6.7bn (Biomedical Counselor 2017). For all other estimates, no credible sources could be found in open literature. Therefore, these were assumed to have similar ratios to the fossil-based pharmaceutical production.

The European market was estimated at €40bn in 2019 (Market Data Forecast 2019). However, no data on individual European countries could be obtained. Therefore, the ratio of the European biopharmaceutical market was assumed to be identical to the European fossil pharmaceutical market. The US market was estimated at €109bn and the Japanese market at €20bn by Scarlat et al. (2015). However, this data is from 2012, and the Japanese market was reduced by €5bn to align the data with the other datasets. The market in Oceania was estimated based on their share of the bio-excipients market (Grand View Research 2020b), resulting in a biopharmaceuticals market of €1.7bn. The South American market was estimated at €24bn in 2018 by Statista (2019e). Without any other sources on biopharmaceutical markets, the remainder of the markets were estimated based on the ratio of the fossil-based pharmaceutical markets.

The overall shares in production and markets are presented in Table 6 and Figure 13. Data from specific countries is presented where available. When no data was available, countries are clustered in larger areas. Due to limited data availability and the combination of data from different sources, using different years and different definitions, care should be taken to only draw conclusions from the general trends presented, and not from the exact numbers. Moreover, since much of the data for the bio-based pharmaceutical market and its production is lacking, it was often assumed that the ratio of bio-based and fossil-based were identical. The ratio should therefore not be included in any conclusions on these production and market numbers until better data sources for this sector are available. Another uncertainty arises from the use of €m as a unit for the production capacity rather than using production volume, which was done for chemicals and plastics. This was done due to the source data being presented only in monetary values. This means that the production of higher value components, specifically active ingredients, have a larger impact on this assessment than the lower value components, such as filler material. When the bio-based economy is promoted, this is often done to promote the environmental benefits of bio-based alternatives, which have the largest impact on products that are produced in larger volumes. Therefore, obtaining data on the volumetric production of bio-based pharmaceuticals would be more insightful, and this is an important data gap in the currently available open data.

Table 6. Market size and production capacity estimate of bio-based and fossil pharmaceuticals in the most relevant regions.

	Bio-based market (€m)	**Fossil market (€m)**	**Bio-based capacity (€m)**	**Fossil capacity (€m)**
Belgium	-	-	1	13
Denmark	-	-	6	14
France	6	28	8	19
Germany	6	31	1	29
Ireland	-	-	-	19
Italy	5	26	-	30
Russia	3	13	-	-
Spain	3	16	-	15
Sweden	-	-	6	-
Switzerland	-	-	5	46
UK	4	21	13	22
rest of Europe	13	64	10	40
Europe total	40	199	50	248
US	109	412	79	236
Rest of North America	5	18	1	161
North America total	114	431	79	397
Brazil	8	15	6	21
Rest of South America	16	30	3	12
South America total	24	46	10	32
China	21	115	44	127
Japan	15	71	-	85
South Korea	1	-	2	14
India	-	-	7	14
Rest of Asia	5	9	23	25
Asia total	42	195	76	266
Oceania total	2	21	5	15
Africa total	2	26	4	15
World total	224	916	224	973

Sources: Data taken from several country specific sources as described in section 5.3. Note: "-" indicates that data is not available.

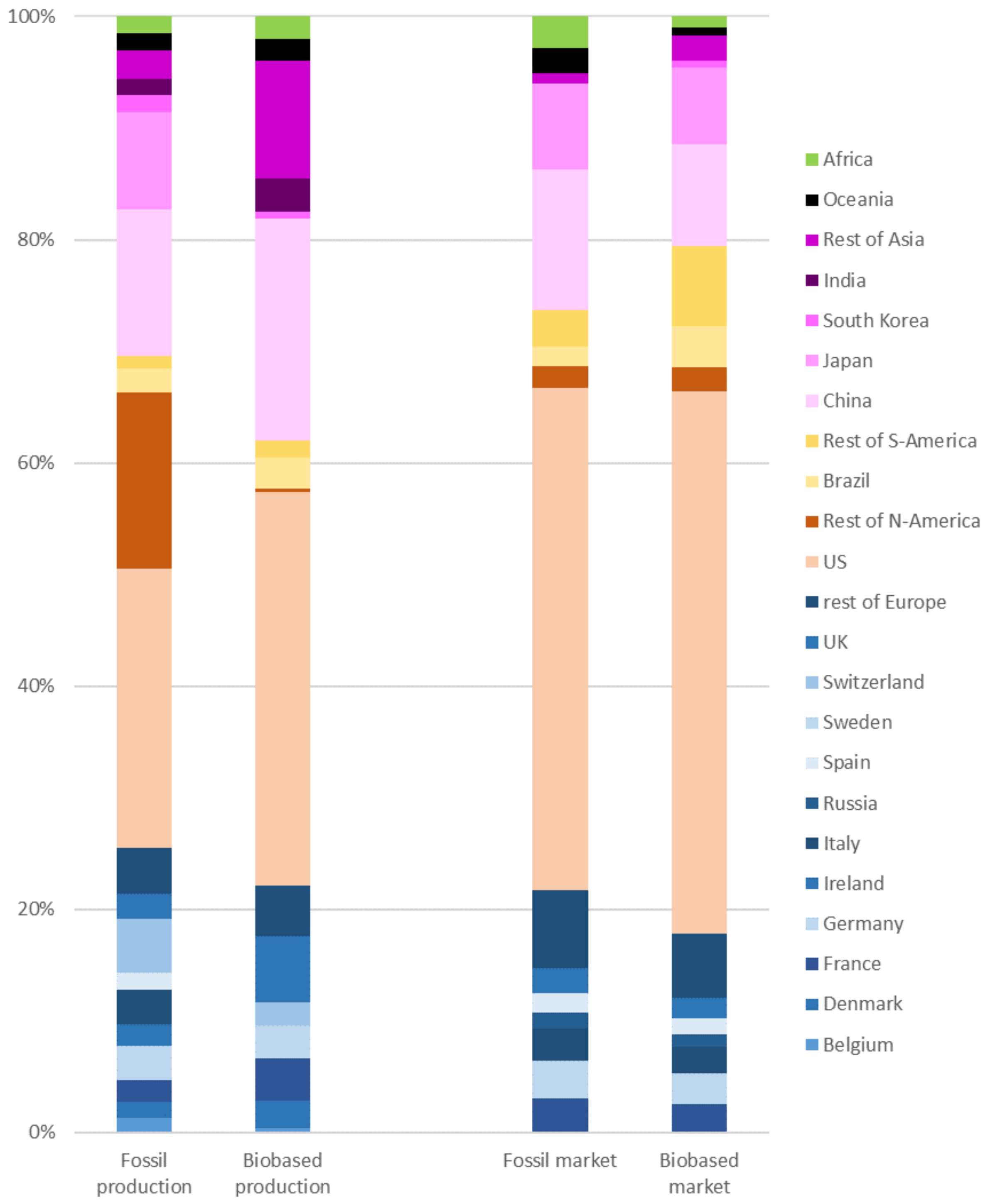


Figure 13. Estimate of the share of important regions for the production and markets of fossil and bio-based pharmaceuticals, both based on €m/y.

Source: Authors' elaboration based on Table 6.

According to Tecnon OrbiChem (2016), production of levulinic acid has been almost entirely in the hands of small producers in China, which has been the only significant source of product. Since 2015, Europe reportedly entered the levulinic acid production at commercial scale. Current production is expected to be somewhere between 3 and 14 ktonnes/year, located in Asia and Europe.

Figure 14 shows that Asia was the largest net exporter of lactic acid, its salts and esters, followed by Europe. This is particularly driven by exports and imports of lactic acid of Thailand and China.

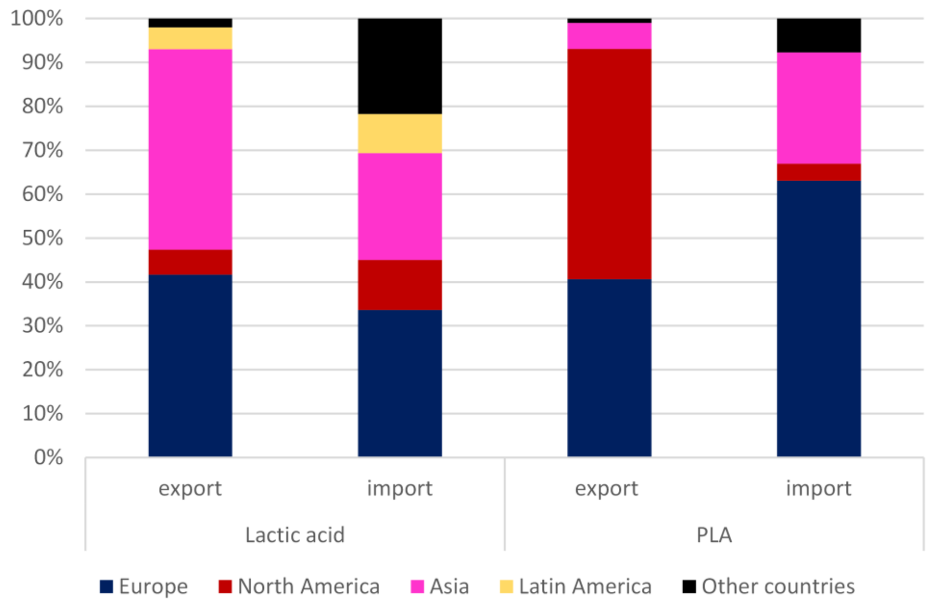


Figure 14. Trade share of lactic acid and PLA by region in 2018. The totals per continent are the totals of the countries in the top20 of exporters or importers. The other export and import fall under “other countries”.

Source: UN Comtrade data as interpreted by ABRAMS (2020).

6 Cost shares at industry level

6.1 Overview

Grouped at industry level (i.e., chemicals, plastics, and pharmaceuticals), the cost-share data has been compared with that of the fossil industries, with a specific focus on sectors, processes, feedstocks, and regions. The key difference is the higher cost shares in feedstock, particularly in the plastics sector and for the use of vegetable oil, where the feedstock costs increase. This can be explained by the higher price of vegetable oil compared to sugar or starch. It should be noted that bio-based cost shares are based on the bio-based products which have successfully reached large-scale production. These results are therefore biased towards bio-based products which can compete with their fossil-based counterparts. The cost shares of all bio-based products, regardless of their successes in large-scale production, would better reveal where the hurdles are for the large-scale production of innovative bio-based products. Table 7 provides a summary of the production and cost information available for the seven selected value chains.

Table 7. Summary of production and cost data collected per value chain (ktonnes/year).

Industrial sector	**Chemicals**			**Plastics**		**Pharmaceuticals**	
Intermediary chemical	**Acetic acid**	**Propylene glycol**	**Succinic acid**	**PET**	**PUR**	**Lactic acid**	**Levulinic acid**
Drop in or dedicated	drop-in	drop-in	drop-in	drop-in	drop-in	dedicated	dedicated
Total (fossil & bio-based) production	16546	2520	50	24059	22334	769	6
Bio-based production ktonnes/year	346	424	10	559	7.5	769	6
- Europe	72	28	10	0	0	149	3
- North America	34	196	0	0	7.5	245	0
- Asia	240	200	0	161	0	375	3
- Rest of the world	0	0	0	0	0	0	0
Bio-based share in total production	2.1%	17%	20%	2.3%	0.03%	100%	100%
- Europe	0.4%	1%	20%	0	0	19%	50%
- North America	0.2%	8%	0	0	100%	32%	0%
- Asia	1.5%	8%	0	100%	0	49%	50%
- Rest of the world	0	0	0	0	0	0%	0%
Price bio-based €/kg	0.94	1.34	2.61	1.13	2.04	1.17	4.50
Price fossil-based €/kg	0.56	1.34	2.25	1.05	1.76	1.75	N/A
Cost disadvantage (-) /advantage (+) ratio	-66.70%	0%	- 16%	-7%	-16%	+ 33%	N/A

Source: Authors' elaboration.

6.2 Comparison of bio-based and fossil-based cost shares

6.2.1 Sectors

This section compares bio-based and fossil-based cost shares for the three sectors of interest (chemicals, plastics, and pharmaceuticals) as shown in Figure 15 to Figure 20. The box plots present the first and third quartile of the data set, with a line at the median. The whiskers represent the minimum and maximum value. The box plots indicate the range of costs depending on the selected regional aggregate for each fossil-based sector and highlight that particularly other feedstock and labour costs lead to region-specific differences impacting the production of fossil-based chemicals and plastics. With regard to fossil-based pharmaceuticals (Figure 17), large regional differences in the costs related to bio-based feedstock and capital can also be observed.

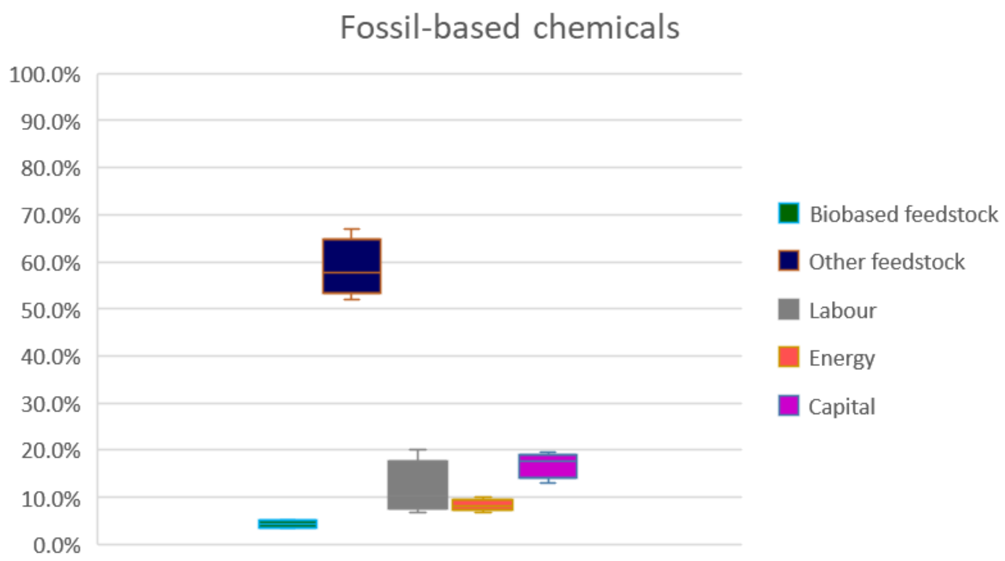


Figure 15. Cost shares of the fossil-based chemical industry of four main regions (Asia, Europe, North America and South America).

Source: Global trade analysis project database version 10, year 2014 (Aguiar et al. 2019).

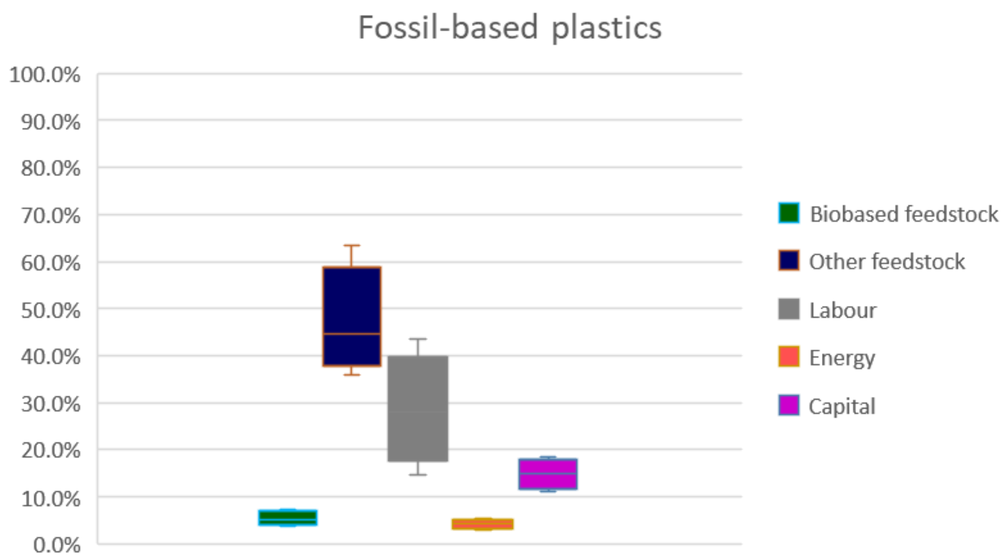


Figure 16. Cost shares of the fossil-based plastic industry of four main regions (Asia, Europe, North America and South America).

Source: Global trade analysis project database version 10, year 2014 (Aguiar et al. 2019).

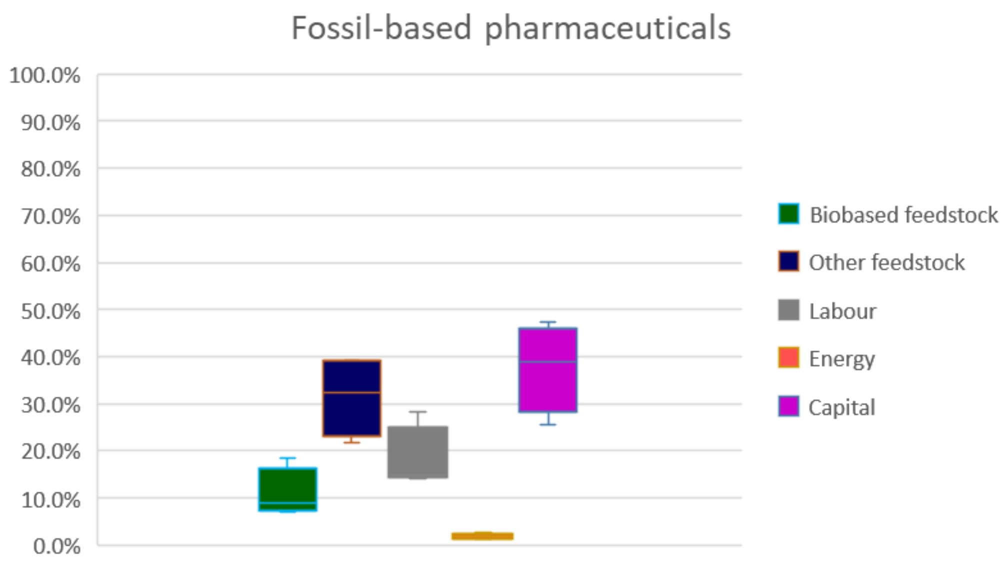


Figure 17. Cost shares of the fossil-based pharmaceutical industry of four main regions (Asia, Europe, North America and South America).

Source: Global trade analysis project database version 10, year 2014 (Aguiar et al. 2019).

The differences between the three fossil-based sectors are relatively small, with the medians usually falling within 10% of each other. There are three notable differences in these cost shares. First, the share made up by fossil feedstock costs is highest for chemicals (58%), followed by plastics (45%), and lowest in the pharmaceutical sector (32%). Other notable differences are the relatively higher share in labour costs for the plastics sector (28%) and the higher share in capital expenditure in the pharmaceutical sector (39%).

The cost shares for the bio-based part of each of these sectors are presented in Figures 18 through 20.

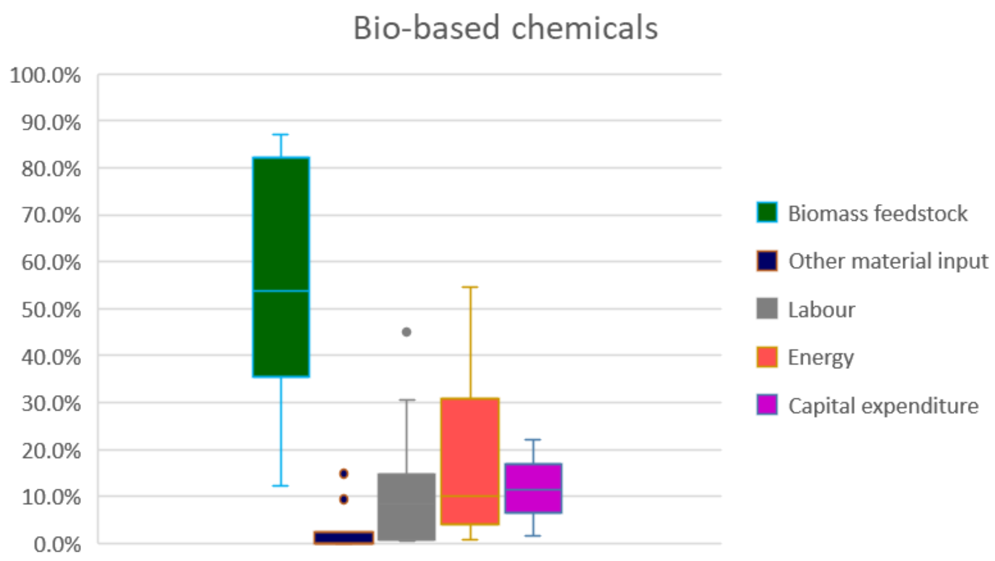


Figure 18. Cost shares of the bio-based chemical industry of the studied value chains.

Source: Authors' elaboration based on selected value chains.

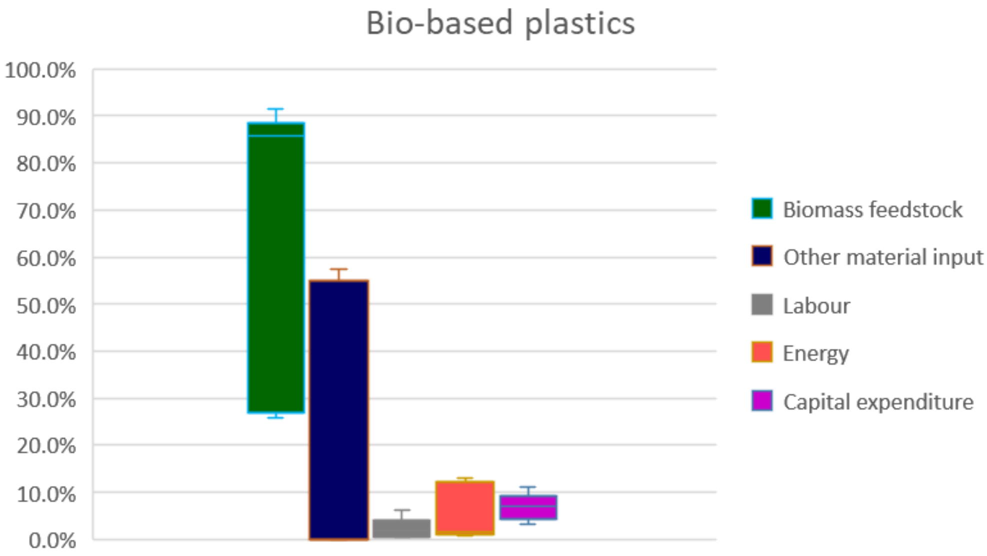


Figure 19. Cost shares of the bio-based plastics industry of the studied value chains.

Source: Authors' elaboration based on selected value chains.

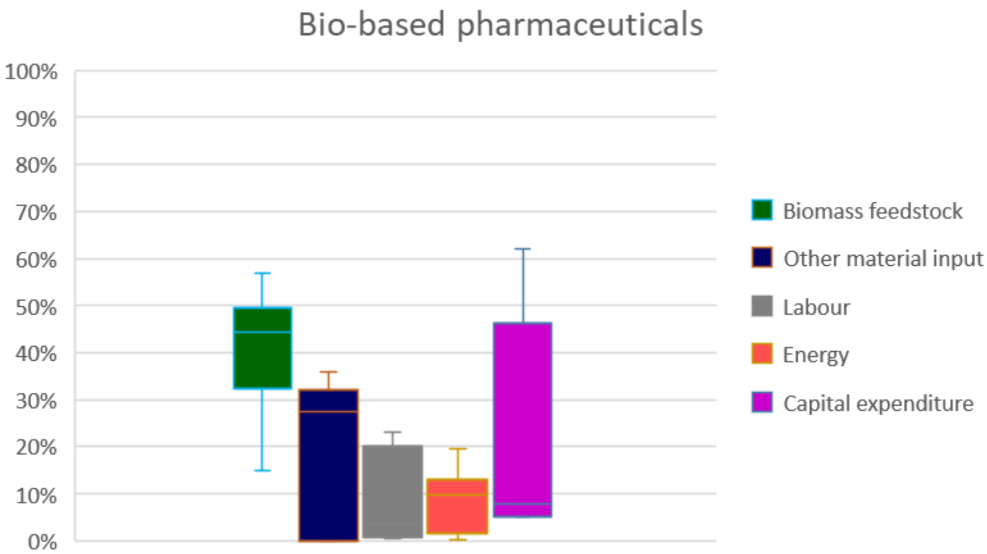


Figure 20. Cost shares of the bio-based pharmaceutical industry of the studied value chains.

Source: Authors' elaboration based on selected value chains.

The bio-based cost shares for chemicals are not strikingly different to their fossil-based counterparts. In particular, the bio-based chemical cost shares are very similar to the fossil-based cost shares. In both cases, the feedstock takes the largest part of the cost share (54% for bio-based and 58% for fossil-based) and the other cost shares have a median of around 10% to 20%. However, in the other sectors, some differences can be observed.

The bio-based plastic sector shows a cost share for feedstocks of 86%, which is much higher than the cost share for feedstocks of fossil-based plastics, at 45%. Note that only two bio-based plastics value chains were evaluated, and this effect could be due to the specific plastics selected (PET and PUR), rather than an effect of the entire bio-based plastics sector. Due to the higher cost share in feedstock, the other cost shares for the bio-based plastic sector are lower in comparison to the fossil-based plastic sector. The high labour costs for fossil-based plastics are not observed in the data set for bio-based plastics.

Finally, the bio-based pharmaceutical cost shares do not show the higher capital expenditure costs (cost share of 8%) found in the fossil-based pharmaceutical sector (cost share of 39%), however, it should be noted that the spread is large, and that the third quartile has a value of 46%. Instead, the cost shares of bio-based pharmaceuticals seem to follow the pattern of the bio-based chemical sector rather than the fossil-based pharmaceutical sector. This can be explained by most pharmaceuticals being produced in the chemical sector, where the pharmaceutical application is one of many applications of the chemical.

6.2.2 Processes and regions

The next thing to investigate is the influence of the different conversion techniques applied in the bio-based industry. Here, the data is sorted by the main conversion technology applied in the value chain. The two main conversion technologies are fermentation and thermochemical conversion.

No large differences can be found between the cost shares of the fermentation and thermochemical pathways. The major difference is the spread for capital expenditure for the thermochemical pathways, indicating that this cost share can be significantly higher for some processes. However, the median of the thermochemical capital expenditure (14%) is the same order of magnitude as the median of the fermentation capital expenditure (7%) and the median value for fossil-based conversions (18%). Another observation is that the energy costs for fermentations seem to be higher (median of 11%) than the energy costs for thermochemical conversions (median of 2%) or the energy costs for fossil conversions (4%).

The cost share for a biorefinery is completely different and cannot be compared to the cost shares for fermentation or thermochemical pathways. In a biorefinery, multiple products are produced, and allocating the costs between the several products is challenging. In the selected case of acetic acid production from a pulp and paper side stream, no additional feedstocks were required. This resulted in the cost share being divided fully between labour (68%), energy (28%) and capital expenditure (4%). For this reason, the cost shares of bio-based acetic acid from pulp and paper waste streams were removed from the other analyses as well.

Another parameter that could influence cost shares is the region of production. Three major production regions were identified, namely Europe, Asia and America, where North and South America were grouped together. The differences for fossil-based value chains between the three main regions are small. There are only two notable differences. First, capital expenditure is higher in America (19%) and Europe (18%) compared to Asia (13%). Second, the cost share of labour in Asia (14%) and Europe (15%) is lower than in America (24%).

Similar region-specific trends can be observed for the bio-based value chains as for the fossil-based value chains. The labour cost share is lowest in Asia (1%), followed by Europe (11%), and is highest in America (24%). However, where the capital expenditure for the fossil-based production is higher in America, this trend was not observed for the bio-based value chains, which have a cost share for capital expenditure in Asia of 7% and 11% in both America and Europe.

6.2.3 Feedstock

The final parameter is the impact of using different feedstocks. First, all processes based on sugar and starch are combined and shown in Figure 21, whilst the processes using vegetable oil as the main feedstock are shown in Figure 22, and finally, the processes based on woody biomass or waste streams are presented in Figure 23. For comparison, all fossil-based data was combined in one box plot, which is shown in Figure 24.

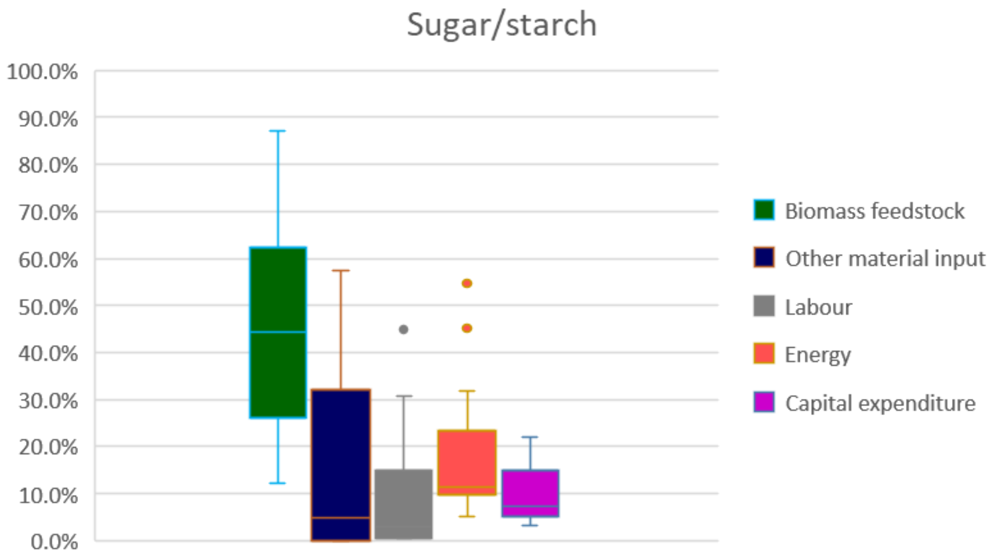


Figure 21. Cost shares of the bio-based value chains based on sugar and starch.

Source: Authors' elaboration based on selected value chains.

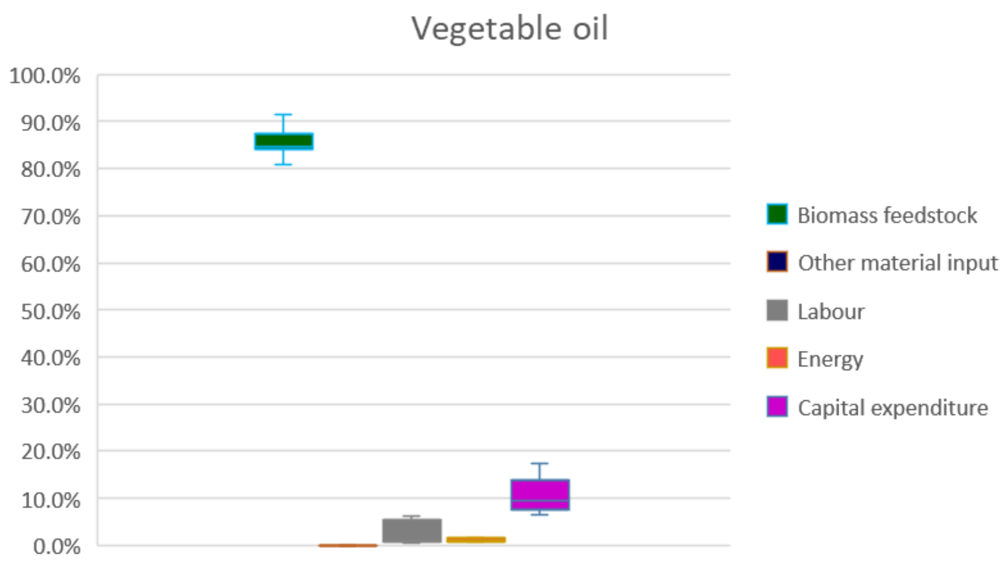


Figure 22. Cost shares of the bio-based value chains based on vegetable oil.

Source: Authors' elaboration based on selected value chains.

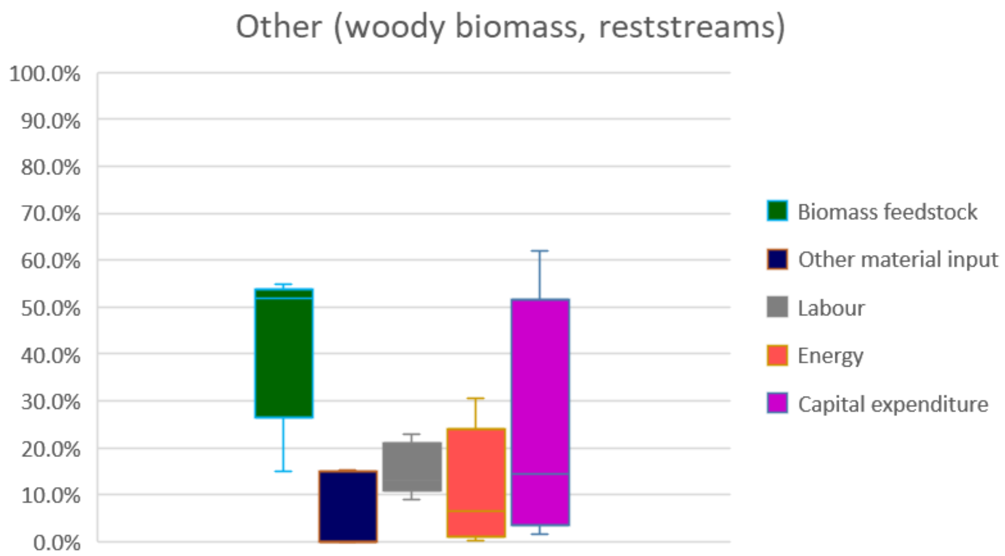


Figure 23. Cost shares of the bio-based value chains based on other feedstocks such as woody biomass and waste streams.

Source: Authors' elaboration based on selected value chains.

The cost shares for bio-based products made from sugars and starch show similar ratios as the cost shares for fossil-based products (Figure 24). The differences from fossil-based products are small with a lower labour cost share (3% for sugar/starch, 15% for fossil), a higher energy cost share (11% for sugar/starch, 4% for fossil), and a lower capital expenditure cost share (7% for sugar/starch, 18% for fossil).

The data for the vegetable oil-based value chains is difficult to obtain and more assumptions are needed to be made for these value chains compared to the sugar and starch-based value chains. However, some big trends can still be observed; for example, the cost share for the biomass input (85%) is much higher than for the sugar and starch-based value chains (45%). Other cost shares are all below 15% and cannot be said to be significantly different due to the large uncertainty in this dataset. A possible explanation can be found in the higher cost price of vegetable oil compared to other bio-based feedstock.

Finally, the cost shares for the value chains based on woody biomass and waste streams follow the fossil-based pattern very closely, with no significant distinctions between these two cost shares.

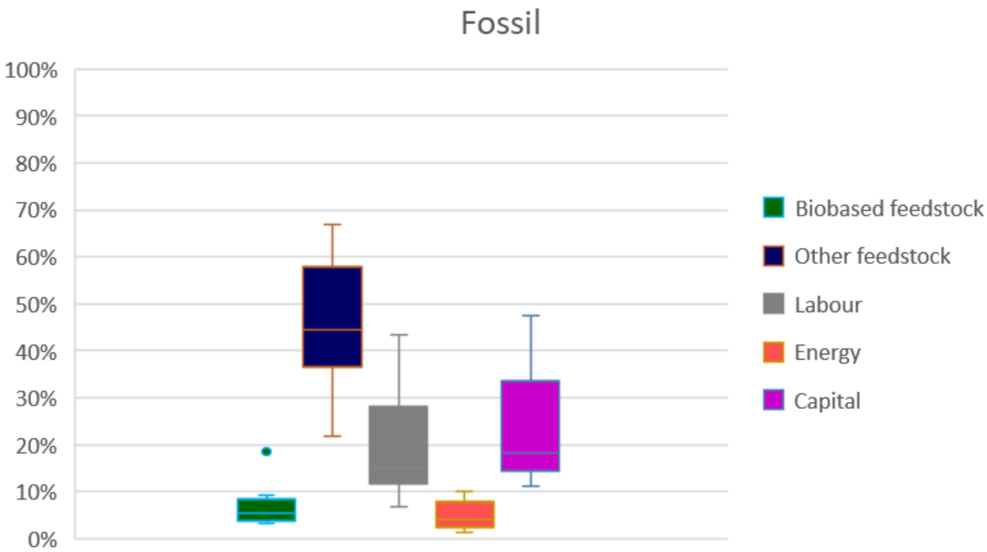


Figure 24. Cost shares of the fossil-based production of chemicals, plastics and pharmaceuticals from the four main production regions.

Source: Global trade analysis project database version 10, year 2014 (Aguiar et al. 2019).

7 Conclusions

Based on a combination of available market reports and other publicly available numbers, the largest share of global fossil-based chemical production takes place in Asia (58%). This number is much higher than the corresponding share in Europe (29%). For total bio-based chemicals however, Europe is much closer to Asia, with a production share of 29% compared to 33% for Asia. Moreover, the same trend can be observed for the market size, with Europe's global share of the bio-based chemical market at 31% compared with its corresponding fossil-based global chemical market share at 16%. Like the trend in production, the Asian fossil-based global chemical market share (59%) is much larger than its corresponding global bio-based market share (30%). Another noteworthy observation is South America, where its global share in bio-based production (14%) is much larger than its global share in fossil-based production (3%). The corresponding statistics for market size are of a similar magnitude (4% of fossil production, 6% of bio-based production).

Total bio-based plastics show a very similar trend to bio-based chemicals. In this sector, Europe plays a greater role in global bio-based production (30%) than in global fossil-based production (17%). The same holds true for the European bio-based market size (36%) compared to the European fossil-based market size (24%). Whilst both North and South American figures for production and market size are broadly similar, the Asian market and production numbers do show significant differences. Here, the global share in bio-based production (42%) is significantly lower than the global share in fossil-based production (57%), and the global share of the bio-based plastic market (30%) is lower than the global share in the fossil-based market (43%).

For the pharmaceutical industry, the data is of a lower quality, which makes it more challenging to reach any firm conclusions. The differences seem to be much smaller than the differences for chemicals and plastics. For example, market reports reveal that the European share of global bio-based pharmaceutical production (22%) is similar to the European share of global fossil-based pharmaceutical production (25%). The same holds true for the European bio-based market (18%) compared with the European fossil-based market (22%).

The overall trend of the three sectors is that the European share of bio-based global production and the global market is larger than its corresponding global shares of fossil-based production and markets. The opposite holds true for Asia, where the global share in bio-based production and markets is smaller than their fossil-based equivalents. The exception is the pharmaceutical sector, where no large differences were observed.

There are some differences between the cost shares of bio-based production and fossil-based production. The most notable difference is the higher cost shares in feedstock, with feedstock costs being especially high in the plastics sector, particularly in the use of vegetable oil. This can be explained by the higher price for vegetable oil compared to sugar or starch.

It should be noted that the bio-based cost shares are based on bio-based products that have successfully reached large-scale production. These results are therefore biased towards bio-based products that can compete with their fossil-based counterparts. Cost shares of all bio-based products, regardless of their successes in large-scale production, would better reveal where the hurdles are for large-scale production of innovative bio-based products.

Another factor to note is that these figures only show the cost shares of the products and not the overall costs. The overall costs of the bio-based products could still be significantly higher compared to the overall fossil-based costs. The influence of factors such as smaller scale and a lower Technology Readiness Level (TRL) level cannot be directly observed in this analysis, since they would affect multiple categories, however, some higher costs could be observed indirectly. Optimisation of the production processes would lower the costs in multiple cost shares as well. However, it is difficult to foresee what the magnitude of the effect is on each of the cost shares and is therefore difficult to identify in this type of analysis.

Overall, the cost shares for bio-based production show comparable trends to the cost shares for fossil-based production. The cost shares show little dependency on the sector, conversion process, or region of production. The type of feedstock used does have an impact and is the main difference between the cost shares for fossil-based and bio-based production, with the use of vegetable oil resulting in higher cost shares for feedstock use.

The outcome of this study is a collection of data on seven representative value chains related to bio-based chemicals, pharmaceuticals and plastics at EU and global level. This database can also serve as a starting point for future activities to improve the representation of bio-based industries in forward-looking modelling tools and thus contribute to improving ex-ante approaches to policy assessments.

References

ABRAMS (2020) : ABRAMS World Trade Wiki, available at https://en.abrams.wiki/tools/marketintelligence?utm_source=partner&utm_medium=website&utm_campaign=uncomtrade.

Ademe (2015): *Marchés actuels des produits biosourcés at évolutions à horizons 2020 et 2030*, available at https://www.ademe.fr/marche-actuel-produits-biosources-evolutions-a-horizons-2020-2030

Aguiar, A., Chepeliev, M., Corong, E., McDougall, R., & van der Mensbrugghe, D. (2019) : *The GTAP Data Base: Version 10. Journal of Global Economic Analysis, 4(1), 1-27.* Available at https://www.jgea.org/ojs/index.php/jgea/article/view/77

Alsaheb, Ramzi, A. Abd., Azzam Aladdin, Nor Zalina Othman, Roslinda Abd Malek, Ong Mei Leng, Ramlan Aziz, Hesham A. El Enshasy (2015), *Lactic acid applications in pharmaceutical and cosmeceutical industries*, Journal of Chemical and Pharmaceutical Research, 7 (10), 729-735.

Beucker, Severin, Frank Marscheider-Weidemann (2007), *Potentials and Challenges of Bioplastics – Insights from a German Survey on "Green" Future Markets*, available at https://www.borderstep.de/wp-content/uploads/2014/12/beucker_marscheider_potentials_and_challenges_of_bioplastics_2007.pdf

Biddy, Mary J., Christopher Scarlata, Christopher Kinchin (2016) Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential.

Bio-based News (2018), *Japan to subsidize bioplastics development*, available at http://news.bio-based.eu/japan-to-subsidize-bioplastics-development/

Biomedical Counselor (2017), *Bio-Pharmaceutical Industry in India*, available at https://biomedicalcounselor.wordpress.com/2017/05/16/bio-pharmaceutical-industry-in-india-market-top-biotech-startup-companies/

BioPlan Associates, Inc 2018, *Report and Survey of Biopharmaceutical Manufacturing Capacity and Production,* available at http://bioplanassociates.com/wp-content/uploads/2018/07/15thAnnualBiomfgReport_TABLEOFCONTENTS-LR.pdf

Biopreferred (2018), *An Economic Impact Analysis of the U.S. Bio-based Products Industry,* available at https://www.biopreferred.gov/BPResources/files/Bio-basedProductsEconomicAnalysis2018.pdf

Cebr (2015), *The future potential economic impacts of a bio-plastics industry in the UK*, a report for the Bio-based and Biodegradable Industries Association (BBIA).

CEFIC (2020a), *CEFIC Facts and Figures,* available at https://cefic.org/app/uploads/2019/01/The-European-Chemical-Industry-Facts-And-Figures-2020.pdf

CEFIC (2020b): *Landscape of the European Chemical Industry 2020 – Italy*, available at https://www.chemlandscape.cefic.org/wp-content/uploads/pdfs/Italy-67.pdf

CEFIC (2020c): *Landscape of the European Chemical Industry 2020 – France*, available at https://www.chemlandscape.cefic.org/country/france/

China Daily (2019), *China's pharma market to gain 30% global share*, available at http://www.china.org.cn/business/2019-12/20/content_75532721.htm

Drug Development & Delivery (2018), *Australian Pharmaceutical Market to Surpass $25 Billion*, available at https://drug-dev.com/australian-pharmaceutical-market-to-surpass-25-billion/

E4Tech (2015), *From the Sugar Platform to Biofuels and Biochemicals: Final Report for the European Commission, Directorate-General Energy. E4Tech (UK) Ltd, Consorzio per la Ricerca e la Dimostrazione sulle Energie Rinnovabili (RE-CORD), Stichting Dienst Landbouwkundig Onderzoek, Wageningen University and Research Centre (WUR).*

EFPIA (2018), *The Pharmaceutical Industry in Figures,* available at https://efpia.eu/publications/downloads/efpia/2018-the-pharmaceutical-industry-in-figures/

Ernst & Young (2013), *Beyond Borders, Matters of Evidence*, available at https://www.ey.com/Publication/vwLUAssets/Beyond_borders/$FILE/Beyond_borders.pdf

European Bioplastics (2018) *Bioplastics market data 2018,* available at https://www.european-bioplastics.org/wp-content/uploads/2016/02/Report_Bioplastics-Market-Data_2018.pdf

European Bioplastics (2020), *Bioplastics market data,* available at https://www.european-bioplastics.org/market/

Fortune Business Insight (2020), *Bioplastics Market Size, Share & Indsutry Analysis*, available at https://www.fortunebusinessinsights.com/industry-reports/bioplastics-market-101940

Global Business Reports (2018), *Introducing Brazil's Chemical Sector,* available at https://www.gbreports.com/article/introducing-brazils-chemical-sector

GlobeNewswire (2019a), *Levels to Propel Bio-Based Chemicals Industry*, available at https://www.globenewswire.com/news-release/2019/04/30/1812656/0/en/Bio-Based-Chemicals-Market-Size-Worth-USD-97-2-Billion-by-2023-at-10-47-CAGR-Lowering-of-Carbon-Emission-Levels-to-Propel-Bio-Based-Chemicals-Industry.html

GlobeNewswire (2019b), *Global Biopharmaceuticals Market Overview, 2018-2019 & Forecast to 2025*, available at https://www.globenewswire.com/news-release/2019/07/19/1885192/0/en/Global-Biopharmaceuticals-Market-Overview-2018-2019-Forecast-to-2025.html

Golden, J.S., R. Handfield, J. Pascual-Gonzales, B. Agsten, T. Brennan, L. Khan, E. True (2018), *Indicators of the U.S. Bio-based Economy,* U.S. Department of Agriculture, Office of Energy Policy and New Uses, Office of the Chief Economist.

Goldstein Research (2019), *African Pharmaceutical Market – Industry Analysis & Forecast 2017 – 2030*, available at https://www.goldsteinresearch.com/report/africa-pharmaceutical-industry-market-size-forecast

Grand View Research (2016), *Bioplastics Market Size, Share & Trends Analysis Report By Product, By Production Technology, Regional Outlook, Competitive Strategies, And Segment Forecasts, 2019 To 2025,* available at https://www.grandviewresearch.com/industry-analysis/bioplastics-industry

Grand View Research (2017) https://www.grandviewresearch.com/industry-analysis/bio-based-polyethylene-terephthalate-pet-industry accessed on 24 April 2020.

Grand View Research (2019a), *Bio-based Platform Chemicals Market Worth $22.75 Billion By 2025*, available at https://www.grandviewresearch.com/press-release/global-bio-based-platform-chemicals-market

Grand View Research (2019b), *Bio-based Platform Chemicals Market Size, Share & Trends Analysis Report By Product, And Segment Forecasts, 2019-2025*, available at https://www.grandviewresearch.com/industry-analysis/bio-based-platform-chemicals-market

Grand View Research (2020a), *Plastics Market Size, Share & Trends Analysis Report By Product, By Application, By Region, And Segment Forecasts, 2020 – 2027*, available at https://www.grandviewresearch.com/industry-analysis/global-plastics-market

Grand View Research (2020b), *Biopharmaceutical Excipients Market Size, Share & Trends Analysis Report By Product, By Region, And Segment Forecast, 2020 – 2027*, available at https://www.grandviewresearch.com/industry-analysis/biopharmaceutical-excipients-market

Hassan I. Moussa, Ali Elkamel, Steven B. Young, Assessing energy performance of bio-based succinic acid production using LCA, Journal of Cleaner Production, Volume 139,2016, Pages 761-769.

ICIS (2010) Polyethylene Terephthalate (PET) production and manufacturing process https://www.icis.com/explore/resources/news/2007/11/06/9076427/polyethylene-erephthalate-pet-production-and-manufacturing-process/

ICIS (2019), George Martin, *Brazil's commercial deficit on chemical products grew by 23% in 2018*, available at https://www.icis.com/explore/resources/news/2019/01/31/10313679/brazil-s-commercial-deficit-on-chemical-products-grew-by-23-in-2018/

ifBB (Institute for Bioplastics and composites) (2019) *Biopolymers facts and statistics*, available at https://www.ifbb-hannover.de/files/IfBB/downloads/faltblaetter_broschueren/f+s/Biopolymers-Facts-Statistics-2019.pdf

IFPMA (International Federation of Pharmaceutical Manufacturers & Associations) (2017), *The pharmaceutical industry and global health, facts and figures 2017* available at https://www.ifpma.org/resource-centre/ifpma-facts-and-figures-report/

Indorama Ventures (2019) Sustainability Report 2018, available at https://www.indoramaventures.com/storage/sustain/report/en/2018-sustainability-report.pdf

Industry ARC (2019), *Biopharmaceutical Market – Forecast*, available at https://www.industryarc.com/Report/9586/biopharmaceutical-market.html

Inkwood Research (2018a), *Europe bio-based chemicals market forecast 2019-2027*, available at https://www.inkwoodresearch.com/reports/europe-bio-based-chemicals-market/

Inkwood Research (2018b), *Asia pacific bio-based chemicals market forecast 2019-2027*, available at https://www.inkwoodresearch.com/reports/asia-pacific-bio-based-chemicals-market/

Jogdand, S.N. (2015), *Current status of bio-based chemicals*. Biotech Support Services (BSS), India.

KHIDI (Korea Health Industry Development Institute) (2018), *Pharmaceutical and Biopharmaceutical Industry in Korea*.

Lammens, Tijs, Jurjen Spekreijse, Ángel Puente, Raj Chinthapalli, Mladen Crnomarkovic (2017) *Bio-based opportunities for the chemical industry*. Longlist available at https://www.roadtobio.eu/uploads/deliverables/d11/RoadToBioD1.1_Appendix_A_Database_of_bio-based_chemicals.xlsx

Larotonda, Fabio D.S. (2009), *Biodegradable films and coatings obtained from carrageenan from Mastocarpus stellatus and starch from Quercus suber*, PhD thesis, University of Porto, available at https://www.scinapse.io/papers/167257651

Market Data Forecast (2019), *Europe Biopharmaceuticals Market*, available at https://www.marketdataforecast.com/market-reports/europe-bio-pharmaceuticals-market

Market Research Blog (2018), *The Growing Pharmaceuticals Market: Expert Forecasts and Analysis*, available at https://blog.marketresearch.com/the-growing-pharmaceuticals-market-expert-forecasts-and-analysis

Market Research Future (2019a), *Bio-based Platform Chemicals Market Research Report – Global Forecast till 2025*, available at https://www.marketresearchfuture.com/reports/bio-based-platform-chemicals-market-6604

Market Research Future (2019b), https://www.marketresearchfuture.com/ reports/levulinic-acid-market-1639, accessed in October 2019

Markets and Markets 2018, *Bioplastics & Biopolymers Market worth $14.92 billion by 2023*, available at https://www.marketsandmarkets.com/PressReleases/biopolymers-bioplastics.asp

MarketWatch 2019, *Bio-Based Chemicals Market 2017 to 2023 Status and Trend by Leading Companies, Regional Outlook,* available at https://www.marketwatch.com/press-release/bio-based-chemicals-market-2017-to-2023-status-and-trend-by-leading-companies-regional-outlook-2019-08-14

Marks, Danny, Michelle Ann Miller, Sujitra Vassanadumrongdee (2020), *The geopolitical economy of Thailand's marine plastic pollution crisis*, Asia Pacific Viewpoint, ISSN 1360-7456.

Medium (2019), *India Bio plastics Market*, available at https://medium.com/@rdagade77/india-bio-plastics-market-8b8da37cf4a6

Mordor Intelligence (2017a), *South America Bioplastics Market,* available at https://www.mordorintelligence.com/industry-reports/south-america-bioplastics-market-industry

Mordor Intelligence (2017b), *Asia-Pacific Bioplastics Market,* available at https://www.mordorintelligence.com/industry-reports/asia-pacific-bioplastics-market-industry

Mordor Intelligence (2018), *European Bioplastics Market*, available at https://www.mordorintelligence.com/industry-reports/european-bioplastics-market-industry

Mordor Intelligence (2019), *Biopharmaceuticals Market,* available at https://www.mordorintelligence.com/industry-reports/global-biopharmaceuticals-market-industry

Nghiem, N.P.; Kleff, S.; Schwegmann, S. (2017) Succinic Acid: Technology Development and Commercialization. Fermentation 2017, 3, 26.

Niaounakis, M. (2015) Chapter 1 - Introduction, Editor(s): Michael Niaounakis, Biopolymers: Processing and Products, William Andrew Publishing, 2015, Pages 1-77.

Nikkei Inc. (2019), *Japan Inc. plays catch up in scramble to bioplastics*, available at https://asia.nikkei.com/Spotlight/Environment/Japan-Inc.-plays-catch-up-in-scramble-to-bioplastics2

Novamont (2016) (ref: Novamont, Mater Biotech fact sheet, available at https://www.novamont.com/public/zip/factsheet_materbiotech_EN_web.pdf

Patel, M.K., Bechu, A., Villegas, J.D., Bergez-Lacoste, M., Yeung, K., Murphy, R., Woods, J., Mwabonje, O.N., Ni, Y., Patel, A.D., Gallagher, J. and Bryant, D. (2018): *Second-generation bio-based plastics are becoming a reality – Non-renewable energy and greenhouse gas (GHG) balance of succinic acid-based plastic end products made from lignocellulosic biomass.* Biofuels, Bioprod. Bioref., 12: 426-441. https://doi.org/10.1002/bbb.1849

Piotrowski, S., Michael Carus, Dirk Carrez (2018), *European Bioeconomy in Figures 2008-2015*, available at https://biconsortium.eu/sites/biconsortium.eu/files/documents/Bioeconomy_data_2015_20150218.pdf

Plastic Institute of Thailand (2014), *Plastics Waste: Current Situation, Policy and Idea Model for Solution",* available at http://www.mpma.org.my/Documents/Plastics%20Waste%20-%20Current%20Situation,%20Policy%20and%20Idea%20Model%20for%20Solution_Kongsak%20Dokbua.pdf

Plastics Europe (2019), *Plastics – the Facts 2019*, available at https://www.plasticseurope.org/en/resources/market-data

Plastics Insight 2017, *Country profile – Brazil*, available at https://www.plasticsinsight.com/export-market/explore-your-market/by-country-profile/brazil/

PR Newswire (2019), *U.S. Chemical Production Fell In November On Weaker End-Use Markets,* available at: https://www.prnewswire.com/news-releases/us-chemical-production-fell-in-november-on-weaker-end-use-markets-300978415.html

Ryberg, Morten W., Alexis Laurent, Michael Hauschild (2018), *Mapping of global plastics value chain and plastics losses to the environment*, available at https://gefmarineplastics.org/files/2018%20Mapping%20of%20global%20plastics%20value%20chain%20and%20hotspots%20-%20final%20version%20r181023.pdf

Sawpan, M.A. (2018) Polyurethanes from vegetable oils and applications: a review. J Polym Res 25, 184 (2018). https://doi.org/10.1007/s10965-018-1578-3

Scarlat, Nicolae, Jean-François Dallemand, Fabio Monforti-Ferrario, Viorel Nita (2015), *The role of biomass and bioenergy in a future bioeconomy: Policies and facts,* Environmental Development 15, 3-34.

Spekreijse, J., Lammens, T., Parisi, C., Ronzon, T., Vis, M. (2019), *Insights into the European market of bio-based chemicals. Analysis based on ten key product categories*, EUR 29581 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98420-4, doi:10.2760/549564, JRC112989.

Statista (2017), *U.S. Pharmaceutical Indudstry – Statistics & Facts*, available at https://www.statista.com/topics/1719/pharmaceutical-industry/

Statista (2019a), *Chemical consumption: worldwide, EU, Germany 2004-2018*, available at https://www.statista.com/statistics/263116/chemical-consumption-worldwide-eu-27-germany/

Statista (2019b), *Total resin production in the United States from 2008 to 2018,* available at https://www.statista.com/statistics/203398/total-us-resin-production-from-2008/

Statista (2019c): *Production of processed plastics in Brazil from 2008 to 2018,* available at https://www.statista.com/statistics/486298/processed-plastics-production-in-brazil/

Statista (2019d), *Pharmaceutical revenue in Asia in 2014, by major country*, available at https://www.statista.com/statistics/417971/revenue-from-pharmaceutical-industry-in-asia-by-major-country/

Statista (2019e), *Biopharmaceuticals market value in Latin America in 2018 and 2023*, available at https://www.statista.com/statistics/790036/biopharmaceuticals-market-value-latin-america/

Sweeting, Jack (1997), *Project Cost Estimating: Principles and Practice*, IChemE, ISBN 0852953801.

Tecnon Orbichem 2016, *Handbook of commercial bio-based chemicals*, available at http://www.orbichem.com/userfiles/World%20Analyses%20Subsforms/Handbook%20of%20Commercial%20Bio-based%20Chemicals_Booklet.pdf

Thailand Board of Investment (2019), *Bioplastics,* available at www.boi.go.th

Transparency Market Research (2019), https://www.transparencymarketresearch.com/pressrelease/lactic-poly-lactic-acid.htm, accessed in October 2019

Tribe, M.A. and R.L.W. Alpine (1986), *Scale economies and the "0.6 rule",* Engineering Costs and Production Economics, 10, 271-278, https://doi.org/10.1016/0167-188X(86)90053-4.

Werpy, T., G. Petersen (2004), *Top Value Added Chemicals From Biomass Volume I – Results of Screening for Potential Candidates from Sugars and Synthesis Gas*.

List of abbreviations and definitions

1,4-BDO	1,4-butanediol
AHR	acid hydrolysis residue
Bntonnes/y	billion tonnes per year
DEG	diethylene glycol
DMT	dimethyl terephthalic acid
EFPIA	European Federation of Pharmaceutical Industries and Associations
ESBO	epoxidised soybean oil
EU	European Union
FAME	fatty acid methyl esters
FDCA	2,5-furan dicarboxylic acid
ifBB	Institute for Bioplastics and Biocomposites
IFPMA	International Federation of Pharmaceutical Manufacturers & Associations
ktonnes/y	kilotonnes per year
MEG	monoethylene glycol
Mtonnes/y	Million tonnes per year
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PLA	polylactic acid
PUR	polyurethane
TA	terephthalic acid
TEG	trimethylene glycol
TRL	Technology Readiness Level
UK	United Kingdom
UN	United Nations
US	United States of America

List of figures

List of tables

Annexes

Annex 1. Details of selection process

The selection was performed based on the long-list of 350 bio-based products developed in the project RoadtoBio (Lammens 2017). Using the three selection criteria above, an expert evaluation yielded a short list of potential products. These products are categorised into three groups. The first group consists of the selected products which are the best candidates for the study based on the selection criteria. The second group is the 'B-list'. In principle, these products are also good candidates for the study but did not make the final selection for the various reasons described below. Finally, some products were excluded. These products were deemed unsuitable for the study after closer inspection since they do not meet the selection criteria. A description of the products and their categorisation into the three groups is given below.

A wide range of bio-based products are available on the market, with the RoadtoBio project alone identifying 350 (Lammens 2017). The majority of these products have a significant market share, and no small selection of products could represent its respective market by majority in production size or revenue. Therefore, without significantly extending the scope of seven value chains, a smart selection needs to be made to obtain a representative sample. The aim was to obtain value chains with different characteristics to compare these value chains, while at the same time having a subset of products with the same characteristics, to observe similarities and trends within this group.

An important factor in the selection process is the representativeness of the selection. However, the bio-based chemical industry consists of more than 350 bio-based chemicals, which makes it impossible to cover a large section with a limited selection of 7 value chains. Moreover, value chains that do post large production numbers are often intertwined with food or fuel production. For example, fatty acid methyl esters (FAME) are produced in significant numbers for the chemical industry (estimated at 116 ktonnes/year, Spekreijse 2019), but FAME would not be a suitable candidate to represent the bio-based chemical industry, since it is used mostly in fuels, with less than 1% being used as a lubricant (Spekreijse 2019). This limits the value chain to bio-based products with lower production numbers, totalling a production of 182 ktonnes/year, which is around 4% of the total production of 4725 ktonnes/year.

Rather than covering a large part of the bio-based chemical industry, representativeness was ensured by selecting value chains from different types of feedstock and key technologies. For each selected value chain, the feedstock and key technology was determined. Next, the number of value chains using a certain type of feedstock were added and presented in Figure 25. Here, the presented number shows the number of times a feedstock is used in the selected value chains, where a percentage represents the distribution of feedstocks in the value chains. For acetic acid, which has two main value chains, both feedstocks and key technologies were awarded 0.5 points. This distribution is compared to the distribution in the bio-based sector. The distribution in the bio-based sector was derived from the 50 chemicals selected in the study 'Insights into the European market for bio-based chemicals' (Spekreijse 2019).

The distribution of feedstocks and the distribution of technologies are presented in Figure 25. In both cases, the distribution in the selection matches the distribution in the bio-based sector well. An important difference is the lower representation of oil crops in the selection. Bio-based chemicals derived from oil crops are not produced in the EU, even though they may have a significant market (Spekreijse 2019).

To represent to the entire bio-based chemical industry, an indirect approach can be taken. Here, the sugar and starch-based industry can be modelled based on the 5 sugar and starch value chains, which represents 39% of the bio-based chemical industry. The oil-based chemicals have a lower representation, with only one value chain selected to represent this fraction constituting 43% of the bio-based chemical industry. However, the oil feedstock is mainly found outside of the EU. Moreover, the innovative bio-based products, where growth is expected, are mostly in the sugar and starch-based chemicals. The oil-based chemicals cover mostly traditional products. Wood and waste feedstocks, used in 12% and 6% of the bio-based chemical industry respectively, are each represented with a value chain as well.

To be able to observe trends within the data set, several sugar and starch-based value chains have been selected. Next to this, to observe differences when different feedstocks are used, value chains from other feedstocks, such as oil, wood and waste, have been selected as well.

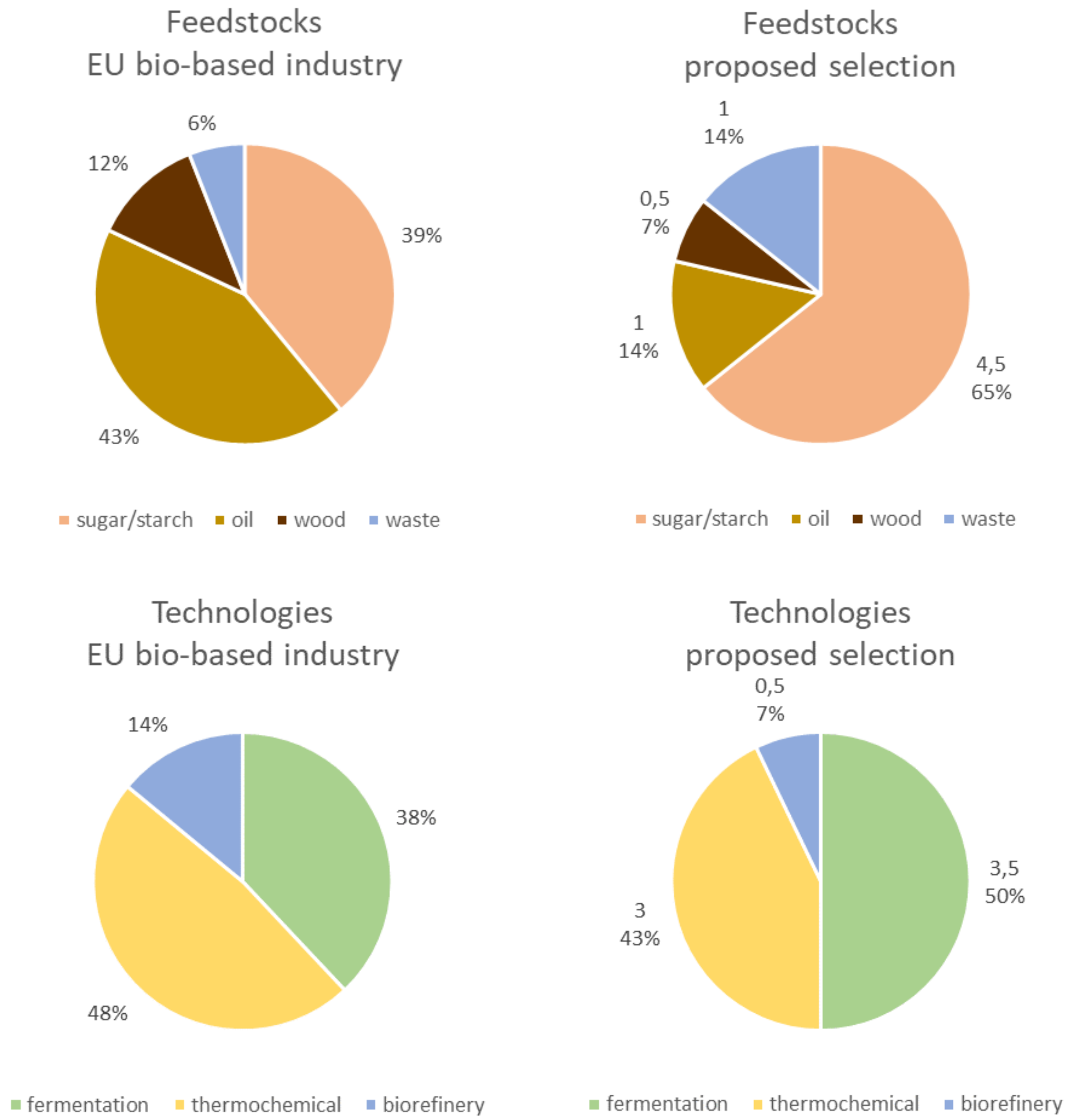


Figure 25. Distribution of feedstocks of the proposed selection compared to the estimated feedstock distribution of the EU bio-based sector. Note: Acetic acid is counted as half for both acetic acid value chains.

Another way to categorise the bio-based chemical industry is by key conversion technology. Here, the main conversion step in the value chain is defined as the characteristic trait of the value chain. This results in three main categories of value chains: fermentation, thermochemical conversion and biorefinery. Here, 4 value chains fall under fermentation (38% of the bio-based chemical industry), 3 value chains fall under thermochemical conversion (48% of the bio-based chemical industry) and 1 value chain falls under biorefinery (14% of the bio-based chemical industry).

Annex 2. Excluded chemicals

B-list chemicals

1,4-butanediol (BDO)

1,4-butanediol is another novel chemical that has multiple end-uses. It is especially important in the production of THF (tetrahydrofuran) and materials for the automotive industry. An important production site of bio-based BDO is in Italy and it is expected that the capacity of the site will grow. However, fermentation of sugar and starch is already well represented by products that have better data availability (i.e., succinic acid and lactic acid), which results in BDO being a B-list chemical in this study.

Furfuryl alcohol

Furfuryl alcohol is an important chemical for the bio-based adhesive industry and has an important production site in Belgium. It is therefore very relevant for the EU. However, furfuryl alcohol is only produced at one site and has only a few applications. This makes the value chain narrow. Moreover, a value chain based on a waste stream is already included in the form of propylene glycol, which makes furfuryl alcohol a B-list chemical.

Itaconic acid

Itaconic acid was already identified as a promising bio-based chemical in the DOE study from 2004 (Werpy 2004). It could have a broad range of applications and would therefore represent the bio-based chemical industry well. Unfortunately, itaconic acid has not yet lived up to expectations. Current production of itaconic acid takes place mostly outside of the EU and production within the EU is still limited. Furthermore, it is assumed that the EU market for bio-based itaconic acid is very small, as no information about it is available.

Excluded chemicals

FDCA (2,5-furan dicarboxylic acid)

Another promising bio-based platform chemical identified in the DOE study is 2,5-furan dicarboxylic acid (FDCA). FDCA could be produced from sugars and would be applied mostly as a replacement for terephthalic acid. This would create PEF, a bio-based alternative to PET. Although there is a lot of interest in both FDCA and PEF, the current production sites are still at ton-scale rather than kiloton-scale. As the other chemicals have larger production volumes and broader applications, FDCA is excluded from this study.

B-list plastics

PLA (polylactic acid)

PLA makes up a significant fraction of global production for bio-based plastics (10%). Unlike PET, PLA is biodegradable, which gives it different applications and markets. Moreover, a biodegradable plastic alongside a non-biodegradable one would give a good representation of the plastics market. In addition, market predictions for bio-based plastics expect PLA to grow significantly in the coming years due to its biodegradability (ifBB 2019). With significant production (7 ktonnes/year) and a significant market in the EU, PLA would be a good choice for this study. However, lactic acid was included due to its applications in both plastics and pharmaceuticals. Therefore, the PLA value chain is included via the inclusion of lactic acid.

Annex 3. Excluded plastics

PHA (polyhydroxyalkanoate)

PHA is another novel bio-based intermediary product that is often cited as a promising bio-based plastic. PHA is produced in the EU and it is also biodegradable, which would make it a good candidate for this study. PHA certainly has a lot of potential for the future, but current production remains low (2 ktonnes/year).

PBS (PolyButylene Succinate)/PBAT (PolyButylene Adipate Terephthalate)

Other promising candidates that were not studied in the previous market study (Spekreijse 2019) are PBS and PBAT. Both of these plastics are often mentioned for their biodegradability; however, they are still produced from fossil-based feedstocks and not from bio-based feedstocks.

Annex 4. Excluded pharmaceuticals

B-list pharmaceuticals

Xanthan

Xanthan is widely used in pharmaceuticals, with nearly 30% of globally produced xanthan ending up in the pharmaceutical industry (Market Intellica 2019). Its main application is as a thickening agent, and for this application it is also used in the food and petroleum oil industries. However, it is not considered a 'novel' bio-based chemical, which makes data availability scarce. In the Insights study (Spekreijse et al. 2019), total production was estimated at 44 ktonnes/year, based on the global production number.

Excluded pharmaceuticals

Terpenes

Many different terpenes are used as active ingredients in pharmaceuticals. Therefore, terpenes are a good group of chemicals to represent the pharmaceutical industry. However, a single chemical rather than a group of chemicals needs to be selected as an intermediary bio-based product. It was found in the previous study (Spekreijse 2019) that information on terpenes, such as limonene, is scarce. Due to lack of detailed information on terpenes, they were excluded from this study.

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: https://europa.eu/european-union/contact_en

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications from EU Bookshop at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

KJ-NA-30653-EN-N

The European Commission's science and knowledge service

Joint Research Centre

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

Publications Office
of the European Union

doi:10.2760/712499

ISBN 978-92-76-32459-1