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Chemical and material driven biorefineries in the EU and beyond

Database and dashboard visualisation

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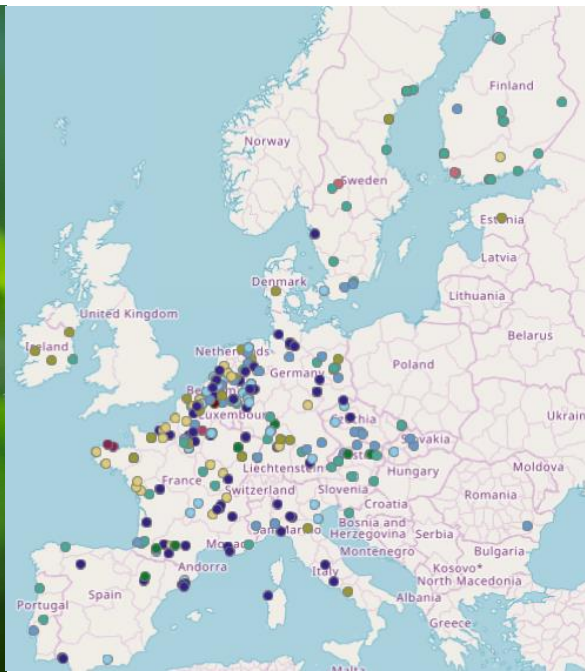
Joint Research Centre



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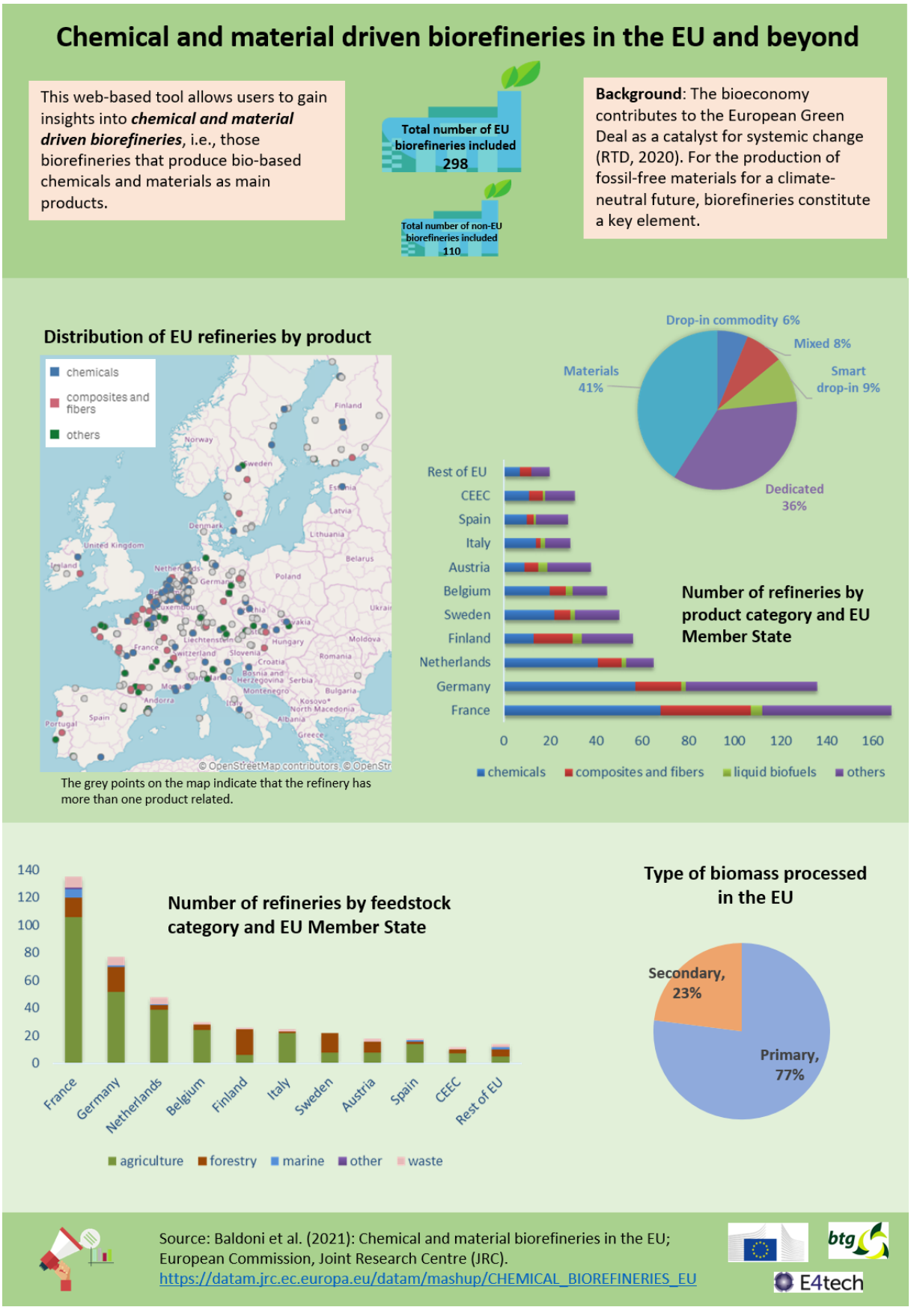
Visual abstract



1 Introduction

The bioeconomy contributes to the European Green Deal as a catalyst for systemic change (RTD, 2020). For the production of fossil-free materials for a climate-neutral future, biorefineries constitute a key element. The 2018 Update of the Bioeconomy Strategy outlines different actions to strengthen and scale-up the bio-based sectors, and unlock investments and markets (European Commission 2018). Biorefining is also one of the key enabling strategies of the circular economy, closing the loop in raw biomass materials (CEAP, 2020).

As shown in this document, of particular interest are chemical and material driven biorefineries, i.e., those biorefineries that produce primarly bio-based chemicals and materials[1]. These bio-based products range from high-value added chemicals and materials such as cosmetics, pharmaceuticals, food additives and others, to high volume chemicals and materials such as general bio-based polymers or chemical feedstocks (i.e. building blocks). Due to their structural role in the manufacturing sector (Baldoni et al., 2021), these products have the potential to contributing substantially to the environmental ambitions of the EU. However, data on this central component of the bioeconomy are still scarce. Data scarcities limit the ability to inform policy-making and to take evidence-based decisions for the development of the bioeconomy (Baldoni et al., 2021).

The present database on chemical and material driven biorefineries in the EU and in selected non-EU countries aims to reduce this data gap. The database builds from the extensive JRC bio-based industry and refineries database (Parisi et al., 2020), and extends it but with a narrower scope as developed in cooperation with the consortium of the Service Contract EC DG-RTD no. 2018/RTD/F2/OP/PP-07281/2018/LC-01369322[2].

For this work, among all those biomass-processing facilities represented in the JRC database, only those that mainly produce chemicals and materials were retained. More traditional bio-based applications such as pulp and paper, wood and energy have been excluded from this new database. Thanks to this narrower scope, the research work could be focused on extending the level of detail for the represented biorefineries. This new level of detail allows for a much more in-depth description of this innovative bio-based sector. Specifically, this new database extends methodologically the previous one in two ways: i) by focusing on the four major structural elements of bio-based pathways (feedstock, conversion processes, platforms and products)[3]; ii) by introducing information on biomass-processing facilities for selected non-EU countries.

These two extensions allow, from one side, to explore in more detail the composition of the bio-based economy in the EU and its implications for sustainability. From the other side, the presence of non-EU bio-based sectors allow international comparisons that can inform stakeholders and policy makers on the comparative development status of bio-based industries in the EU with respect to relevant countries outside the EU that may have different approaches.

The database contains information on location, feedstock, platforms, conversion processes, and products of 298 existing chemical and material driven biorefineries in the EU and of 110 chemical and material driven biorefineries outside the EU. The content of the database is accessible through two separate online dashboards: one dedicated to EU countries and the other dedicated to selected non-EU countries. The decision to separate the visualizations of these two parts of the database was taken due to the different coverage level. As the EU database was built on top of the JRC bio-based industry database, its scope is extensive. Of the 2,362 biomass-processing facilities, all those under the scope of this study were selected. Moreover, a few additional ones have been added. Therefore, the final database should be considered almost exhaustive of the population of chemical and materials driven biorefineries in the EU. Although, it should be noted that this updated database still might not contain all chemical and material driven biorefineries, because of various reasons such as non-availability of information, new developments, etc. (Platt et al., 2021).

On the other side, the non-EU database was built anew. Specific countries were selected based on their importance and based on literature searches (Platt et al., 2021). Data on biorefineries for these countries were limited only to the major or more easily accessible biorefineries. Therefore, we believe the coverage of non-EU

[1] The main product of biorefineries is defined on a mass basis. Chemical and material driven biorefineries may produce energy as a side-product. Biorefineries that focus on the production of energy and that produce chemicals as co-products are not considered in this study.

[2] Biorefinery Pathways and outlook for deployment, Studies on support to R&I policy in the area of bio-based products and services | LOT3; Service Contract EC DG-RTD; no. 2018/RTD/F2/OP/PP-07281/2018/LC-01369322. The final deliverable of the project, divided into several working packages, is provided in Platt et al. (2021). The selection and update of chemical and material driven biorefineries has been provided in particular by Biomass Technology Group BV (BTG) in WP4 of Platt et al. (2021).

[3] A classification of biorefineries as well as the definition of the different pathways has been provided by Wageningen University & Research (WUR) in WP1 and WP3 of Platt et al. (2021).

countries to be lower than that of EU countries. Still, to allow some comparisons between these EU and non-EU countries, each of the two dashboards contains an additional sheet with several comparative visualization. Due to the different coverage levels, these comparisons were made only by looking at the composition of the population of biorefineries in the EU and outside the EU.

Both dashboards have the same structure and are composed of the same four sheets:

1. the geographical distributions of biorefineries («Bio Refineries Plants») together with the distribution of feedstock and product type, as well as of other relevant indicators;
2. the value-chains of biorefineries («Bio Refineries Uses»). Here, the distribution of feedstock, conversion processes, platforms and products are presented altogether to allow for an in-depth navigation though these innovative value chains;
3. a break down of the composition of this bio-based sectors by country and the ranking countries by number of biorefineries («Countries Data»);
4. comparative visualizations for EU and non-EU countries («Comparisons»). Given the different coverage for these two parts of the dataset, only the composition of the bioeconomy are compared across countries. The number of biorefineries by country is also provided in order to shade light on the representativeness of the comparisons.

Figure 1 shows the first sheet of the dashboard together with the sheets menu on the top right corner. In addition to the four sheets, the dashboard menu presents a citation text sheet where authors and other details are presented.

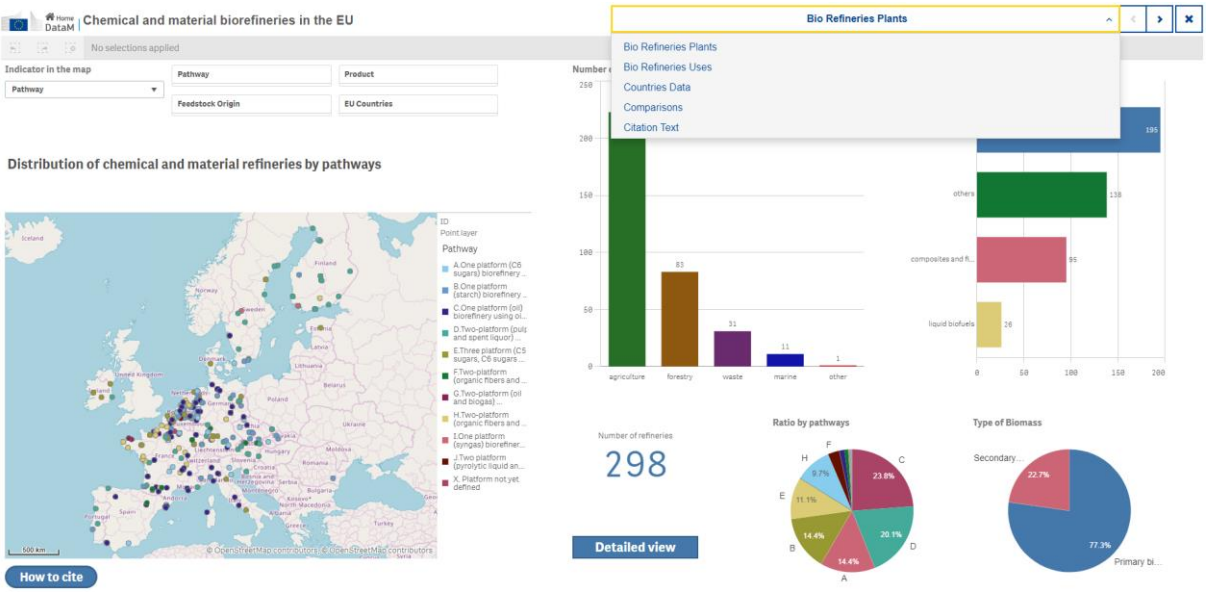


Figure 1. Dashboard overview

For consistency with the existing JRC bio-based industry and refineries database and dashboard, the default visualizations of both dashboards present general feedstock and products categories. These allow for a simplified representation of the distribution of chemical and material driven biorefineries and a quick inspection of relations. However, a more detailed overview of this sector can still be achieved by switching from these general categories to more detailed categories. For that purpose, a general/detail view button that breaks down feedstock and product categories into more detailed ones is provided throughout the dashboards. This additional level of detail of products and feedstock categories is an important extension with respect to the previous JRC database.

2 Scope and definitions

This document aims to present an updated overview of the distribution of the bio-based industry in the EU, with a narrower scope compared to the previous work of the JRC (Parisi 2018 and Parisi 2020).

The focus of the current study is those chemical and material driven biorefineries (incl. also uses of biogenic effluent gases, such as CO_2 and CO) that include the production of innovative high value bio-based products or high-volume ones (i.e., building blocks). Chemical and material driven biorefineries are defined as producing bio-based chemicals and materials as their main products. This means they produce primarily bio-based chemicals and/or materials with bioenergy as a side-product. This also means that bioenergy (power, heat/cold, biofuels) focused facilities that produce chemical co-products are not included. Only commercial, first-of-a-kind and demonstration plants were included (TRL 8 and above). Pilot plants were excluded from the database.

In terms of geographical coverage, the database contains biorefineries in the EU and in ten selected non-EU countries.

The EU part of the database builds on the JRC database and therefore, it is quite extensive. It is considered as representative of the EU population of chemical and material biorefineries. To select the biorefineries that fit the scope of the current study, a set of selection criteria was developed and applied to the JRC database[4], as follows:

- Biorefineries not at TRL 8 or TRL 9 (Technology Readiness Level) were not retained.
- To identify the chemical biorefineries, use was made of the list of the top 120 biochemicals produced in the EU, developed in the RoadToBio project (See Annex I). For these bio-based chemicals, the corresponding biorefineries were selected from the JRC database. This approach has the advantage that it is clear that all or nearly all chemical biorefineries are included in the database.
- To identify the material biorefineries, a list of keywords for bio-based materials were defined (See Annex II) by drafting selected 'word clouds' from the JRC database. Biorefineries in which these biomaterials were listed as products were selected from the JRC database.

Based on the data sources listed above, the JRC database was updated and expanded. The new EU database currently contains 298 entries. It should be noted that this updated database still might not contain all innovative chemical and material biorefineries in the EU (and in the selected non-EU countries), because of various reasons such as non-availability of information, new developments, etc.

The above underlines the difficulty of collecting and maintaining reliable biorefinery information that is time sensitive and/or commercially sensitive. This is hardly surprising and a common problem that anyone building a database for any kind of economic sector is experiencing.

Concerning the non-EU part of the database, ten countries were selected based on their relevance and the database was built anew (Platt et al., 2021). The ten countries selected were: Australia, Canada, Japan, United States, Brazil, China, India, Thailand, Norway and United Kingdom.

To extend the database with additional new biorefineries in the EU and to find information for the selected non-EU countries, several data sources have been explored. Particular attention was given to the following sources:

- "Map of biorefineries in Europe" BIC/NOVA (2017, http://bio-based.eu/graphics/)
- E4tech database for the sugar platform
- Niaounakis, M. Biopolymers: Processing and Products, 2015 (http://dx.doi.org/10.1016/B978-0-323-26698-7.00001-5)
- IEA Task 42 Biorefining country reports, (https://www.iea-bioenergy.task42-biorefineries.com/en/ieabiorefinery/Country-Reports.htm)

[4] Data sources of the JRC database can be found in Parisi (2020).

- De Jong, Bio-based chemicals: a 2020 status update. IEA Task 42 Webinar presentation. (https://www.ieabioenergy.com/ieaevent/iea-bioenergy-webinar-bio-based-chemicals-a-2020-status-update/)

- Rosales-Calderon and Arantes, "A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol", Biotechnology Biofuels (2019) 12:240, (https://doi.org/10.1186/s13068-019-1529-1)

- Spekreijse et al., "insights into the European market for bio-based chemicals", JRC report, 2019, (http://publications.jrc.ec.europa.eu/repository/handle/JRC112989)

Moreover a list of media that were inspected are:

- Bio-based News (http://news.bio-based.eu/)

- Bioplastics News (https://bioplasticsnews.com/top-bioplastics-producers/)

- Biofuelsdigest (https://www.biofuelsdigest.com/)

- Greenchemicalsblog (https://greenchemicalsblog.com/)

- List of Flagship projects BBI (https://www.bbi-europe.eu/projects)

3 Results

The content of the database can be accessed through two online interactive dashboards:

- one for EU countries: https://datam.jrc.ec.europa.eu/datam/mashup/CHEMICAL_BIOREFINERIES_EU/index.html, and
- one for the selected non EU-countries: https://datam.jrc.ec.europa.eu/datam/mashup/CHEMICAL_BIOREFINERIES_NON_EU/index.html.

In this section, the dashboard function and the interpretation of the statistics presented will be shown, together with some main patterns in the data.

The design of the dashboard was meant to present several features of chemical and material driven biorefineries. In general terms, we can categorize these features into three groups:

- a geographical distribution of biorefineries together with some main characteristics (products, and feedstock types);
- a focus on the value chains of biorefineries where the four main elements of pathways are presented altogether (feedstock, conversion process, platform, product);
- an international comparison where the composition of the biorefineries population of the EU is compared with that of selected non-EU countries.

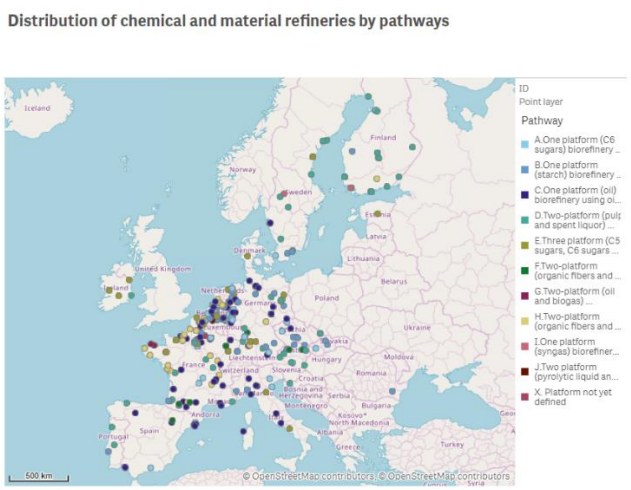
The following three subsections present these three features.

3.1 Geographical distribution and main characteristics of biorefineries

Both dashboards allow for the visualization of the geographical distribution of biorefineries on a map. Different indicators can be selected and visualized. As the design of the two dashboards is the same, here we will focus on the EU dashboard to illustrate their functionality. Figure 2 shows the data field selector at the top of the first dashboard sheet ("Bio Refineries Plants").

Figure 2. Data field selector

By default, the distribution of biorefineries by pathway is visualized on the map. A **biorefinery pathway** is the attribute that better synthesizes value chains of biorefineries. In this work, the central element used to define the different pathways is the one of platform. This central element has been combined with information on feedstock types and product types in order to come up with complete pathway definitions (Platt et al., 2021). Eleven pathway classes are presented in the database and these classes follow the classification of biorefineries proposed by WUR in WP3 of the Lot 3 study (Platt et al., 2021). Classes from A-D represent all those pathways that are available commercially. Pathways E-K are those that have not yet reached a commercial scale (Platt et al., 2021).



Pathway	Number
C.One platform (oil) biorefinery using oil crops, wastes and residues	71
D.Two-platform (pulp and spent liquor) biorefinery using woody biomass	60
A.One platform (C6 sugars) biorefinery using sugar crops	43
B.One platform (starch) biorefinery using starch crops	43
E.Three platform (C5 sugars, C6 sugars and lignin) biorefinery using lignocellulosic biomass	33
H.Two-platform (organic fibers and oil) biorefinery using natural fibers	29
F.Two-platform (organic fibers and organic juice) biorefinery using green biomass	9
G.Two-platform (oil and biogas) biorefinery using aquatic biomass	4
I.One platform (syngas) biorefinery using lignocellulosic biomass and municipal solid waste	3
Others	3
Total	298

Figure 3. Distributions of biorefineries by pathway in the EU

Figure 3 shows the distribution of biorefineries by pathway on the map and their frequency distribution. In the EU, the most frequent pathway is represented by pathway C “One Platform (oil) biorefinery using oil crops, wastes and residues”.

The interactive property of the dashboard allows the user to drill-down into a specific subset of the database simply by clicking on any of the classes of each visualization. For example, to focus on the geographical distribution of only one pathway and visualize it on the map, the user could click on one of the classes in the legend of the map and the dashboard will update automatically by showing only that pathway class. By doing so, it becomes clear how pathway C is geographically concentrated in Belgium, the Netherlands, Germany and France. The second most frequent pathway is represented by D “Two-platform (pulp and spent liquor) biorefineries using woody biomass”. Pathway D seems to be less concentrated geographically than pathway C. In fact, these biorefineries seems to be more evenly distributed across Finland, Sweden, Germany, France, and Austria. Other frequent pathways in the EU are those based on sugar and starch crops (pathway A and B), pathway E and H. Overall in the EU[5], the largest share (72.8%) of innovative chemical and material biorefineries belong to one of the categories of commercially available pathways (A-D).

Together with the attribute pathway, to get a full description of the value chain of biorefineries, feedstock and products of biorefineries can be selected as indicator to be shown on the map. Figure 4 presents the maps of the available general product classes shown altogether and as separate products classes.

[5] Note that this updated database still might not contain all chemical and material biorefineries, because of various reasons such as non-availability of information, new developments, etc. (Platt et al., 2021).

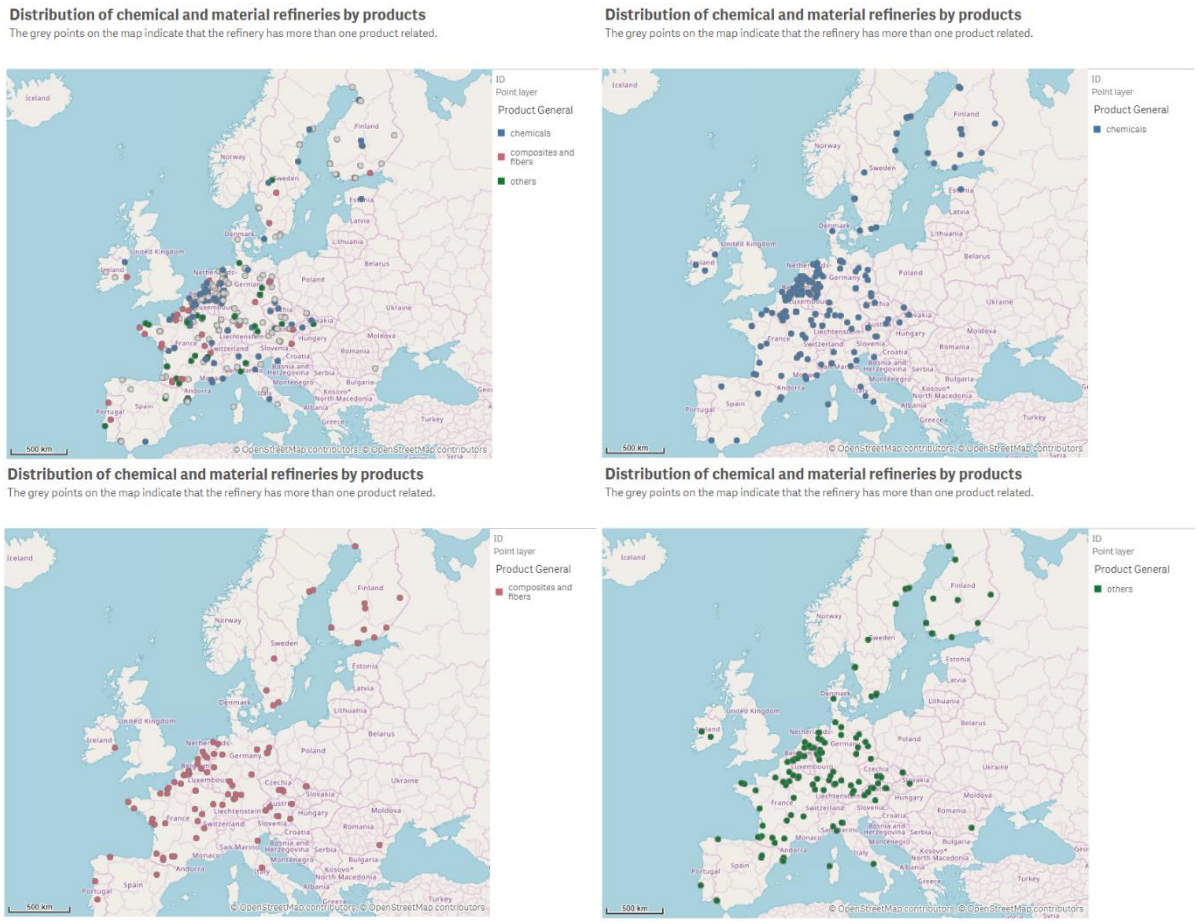


Figure 4. Map of the distribution of the bio-based industry in the EU (by general product classes)

Four general **product classes** are available: chemicals, materials, other, and multiple products. As a biorefinery can produce more than one category of products, the multiple-product class was created to visualize those multi-product biorefineries using a single pair of coordinates on the map. As previously described, by selecting a specific product class on the legend of the map, the dashboard drill down into the specific subset of the database that concerns biorefineries producing that product.

Figure 4 shows the distribution of biorefineries by product class. Figure 4 shows that the large majority of chemical biorefineries are located in France, Germany and the Netherlands while the distribution of material biorefineries seems to be less geographically concentrated. Still, France, Germany and Finland are the leading countries in terms of number of biorefineries producing materials and composites. The product category "other" was meant to capture all those products that fall outside the main categories of chemicals and materials. Examples of these other categories are agrochemicals, feed, pharmaceuticals and other bio-based products. Figure 4 shows that even for this residuals category, the geographical distribution of biorefineries is less concentrated that that of chemicals biorefineries.

The general product classes have been created to simplify the visualization and to create consistency with the previous JRC dashboard. However, the current database contains a higher level of detail for both product and feedstock classes. Therefore, to visualize the detailed product classes that compose each general product class, the user can use the General/Detail switch button. This button can be found throughout the dashboard and it is meant to move from the general product and feedstock categories to the detailed product and feedstock categories that are one of the salient features of this new database. Figure 5 shows the overview of the "Bio Refineries Plants" sheet and highlights the General/Detail view button.

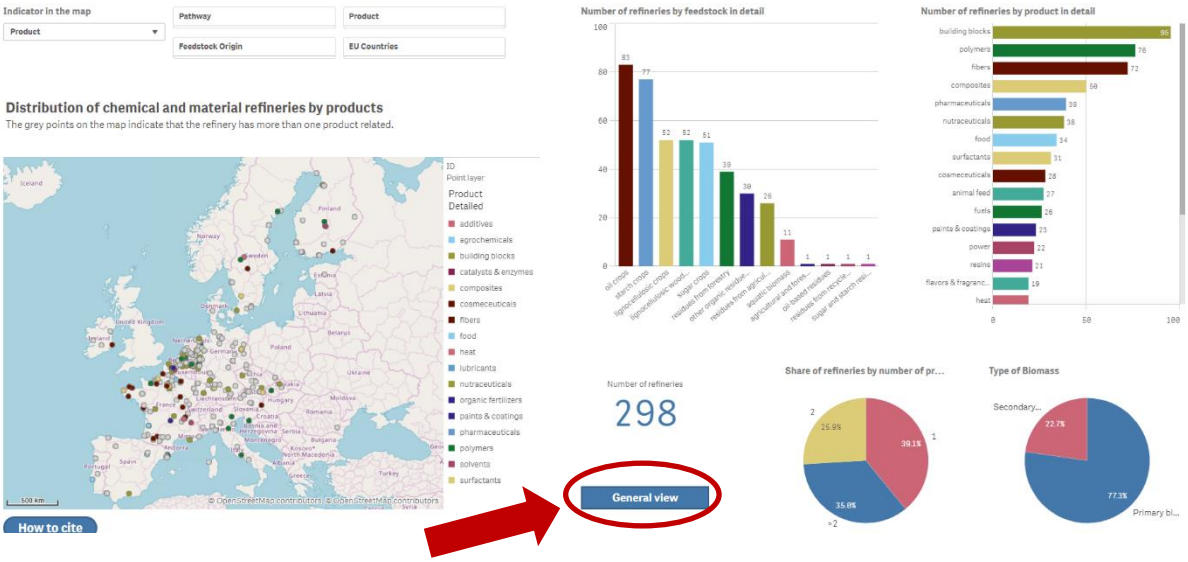


Figure 5. "Bio Refineries Plants" sheet and General/Detailed view button

This switch button unveils the relationship between general product and feedstock categories, and the detailed ones. Figure 6 shows the relationships that exists between the general chemical category and the detailed chemical categories. By selecting chemicals and then switching to the detailed view the distribution of product categories breaks down into its specific components. As it is possible to see from Figure 6, the chemical category is composed of nine specific categories: building blocks, polymers, surfactants, paints & coatings, resins, lubricants, colorants, solvents, and additives.

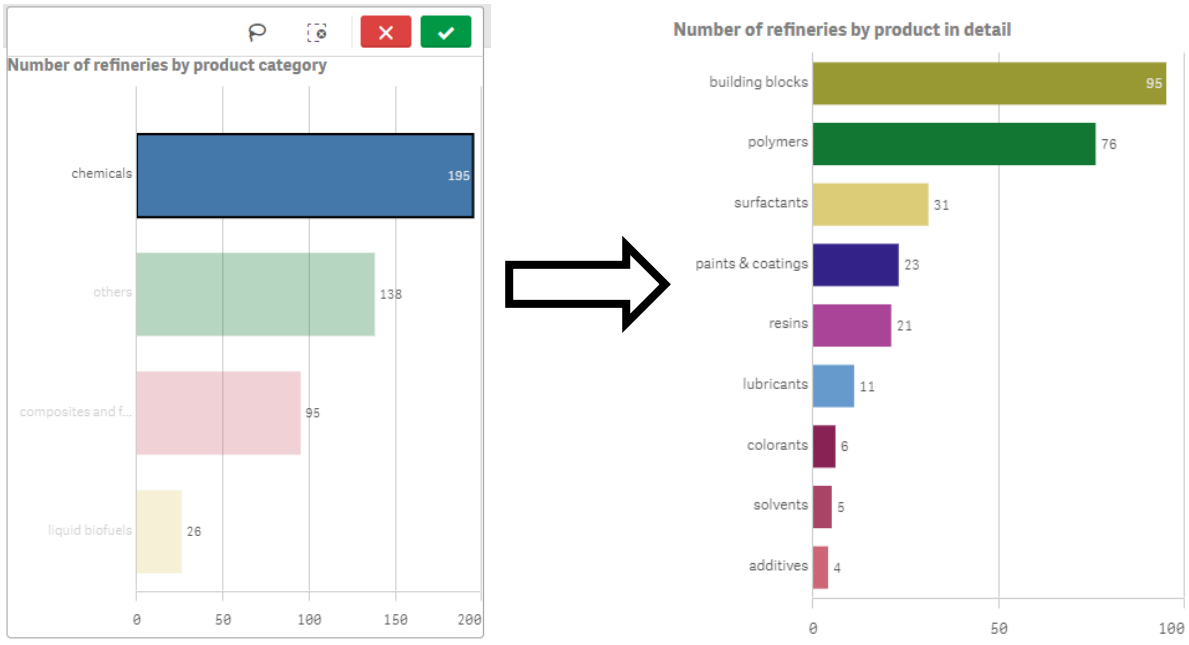


Figure 6. Relationship between general and detailed chemical product classes and their distribution in EU biorefineries

Note that the number of general chemical products is 195. This number represent the number of facilities that produce at least one of the detailed chemical products on the right hand side of Figure 6. But one facility may produce more than one detailed chemical product. In the case a biorefinery produces more than one detailed chemical product, the number of chemical products between the general category and the detailed category will differ. This is the case of Figure 6, where the number of aggregate chemical products is 195 while the

number of specific chemicals is higher (272). This is because any biorefinery may produce more than one detailed chemical product.

In the same fashion, by clicking on the general category "composites and materials" and switching to the detailed view, it is possible to see that this general category is made of only two detailed categories: composites and materials. Figure 7 presents this categorization.

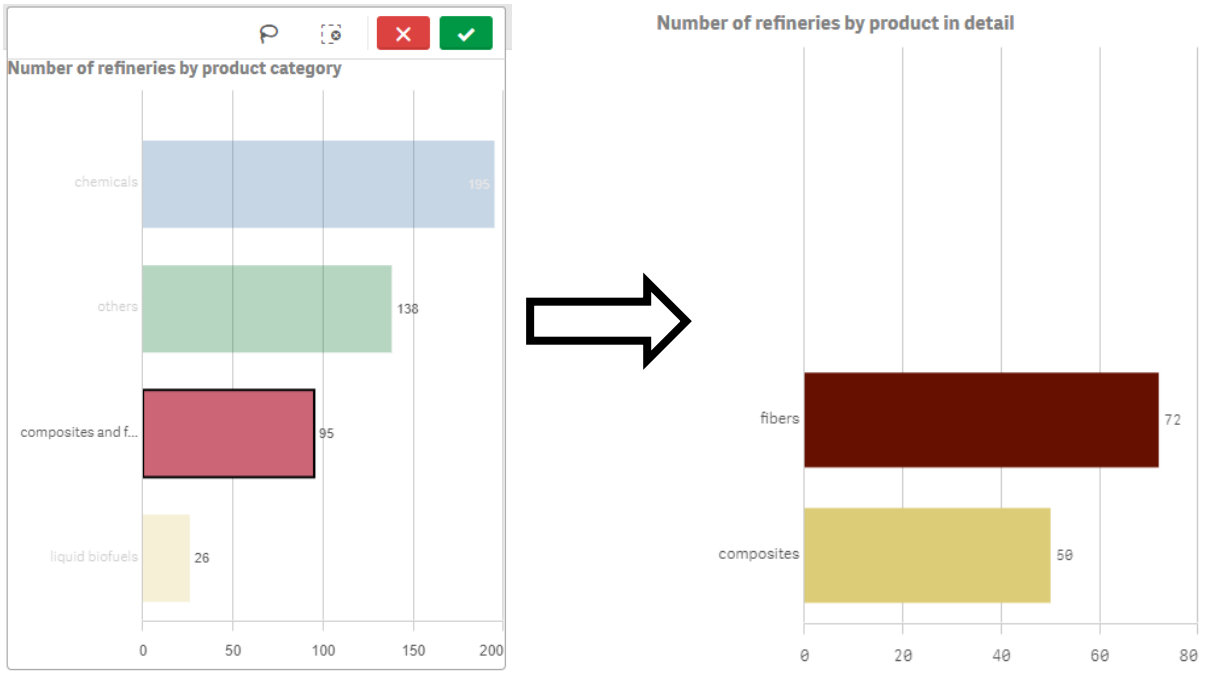


Figure 7. Relationship between general and detailed composites and materials product classes and their distribution in EU biorefineries

In addition to products, the geographical distribution of biorefineries is also presented by **feedstock categories**. By choosing "feedstock" among the list of indicators available (see Figure 2), the map presents the location of biorefineries and qualify them by their feedstock class. Figure 8 presents the general feedstock classes available. These are agriculture, forestry, marine, and waste. A multi-feedstock category is also available here and presented on the map in grey.

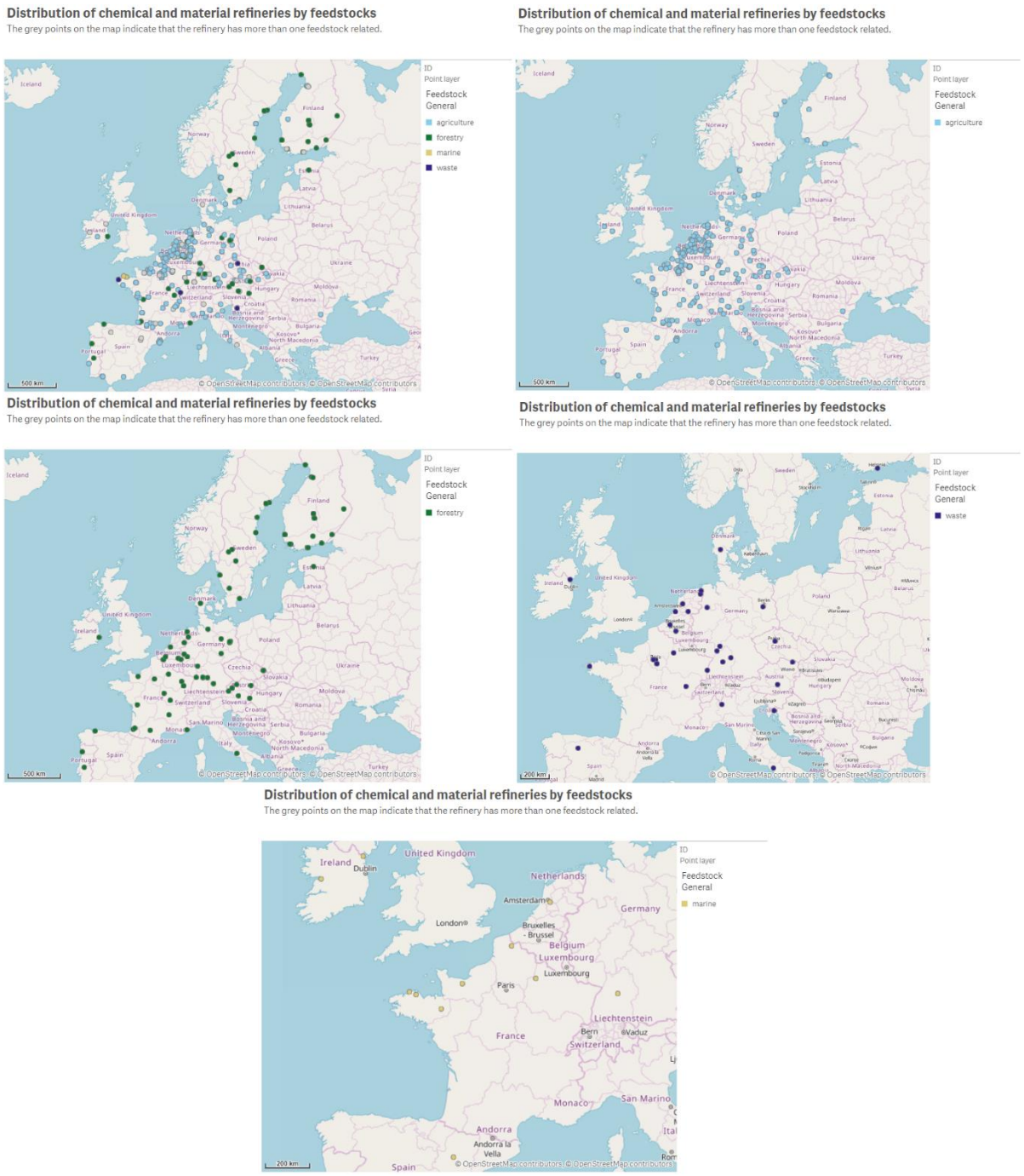


Figure 8. Map of the distribution of the bio-based industry in the EU (products)

As shown in Figure 8, agricultural feedstock is the most widely used general feedstock class in the EU. France and Germany are those countries with the highest number of biorefineries that use agricultural feedstock. Agricultural feedstock-based biorefineries are highly concentrated in the Netherlands and in Belgium. Forestry-based biorefineries are more evenly distributed across EU member states instead, with a substantial share in Finland and Sweden. Waste-based biorefineries are mainly concentrated in Germany, France and the Netherlands. The relatively small number of marine-based biorefineries represented in the database can be found in France, Ireland, Germany, the Netherlands and Spain.

As it was the case for the product classes, the dashboard allows for a more detailed overview of the feedstock types using the General/Detailed switch button. Figure 9 presents the detailed categories linked to the general feedstock category “agriculture”. Figure 9 shows that the most widely used agricultural feedstock type in the

EU is represented by oil crops (83 biorefineries) followed by starch crops (77 biorefineries), lingo-cellulosic crops (52 biorefineries) and sugar crops (51 biorefineries). The remaining agricultural feedstock types are represented by residues (2nd generation feedstock) and they are characterized by a significantly lower number with respect to first generation ones.

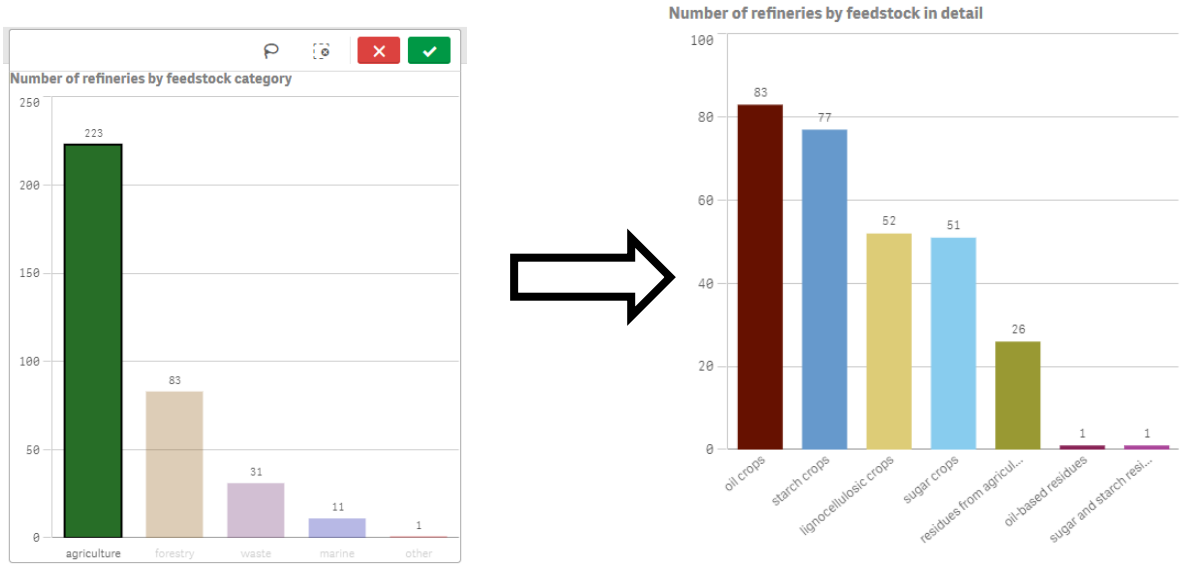


Figure 9. Relationship between general and detailed agricultural feedstock classes and their distribution in EU biorefineries

These insights can be useful when assessing the environmental dimension of sustainability of this sector. To help this assessment, an additional visualization on detailed feedstock categories is provided in the dashboard[6]. This visualization is included in Figure 10 where the distribution of detailed forestry feedstock classes is presented together with a pie-chart that shows the shares of those feedstock classes in terms of their type (1st generation versus 2nd generation).

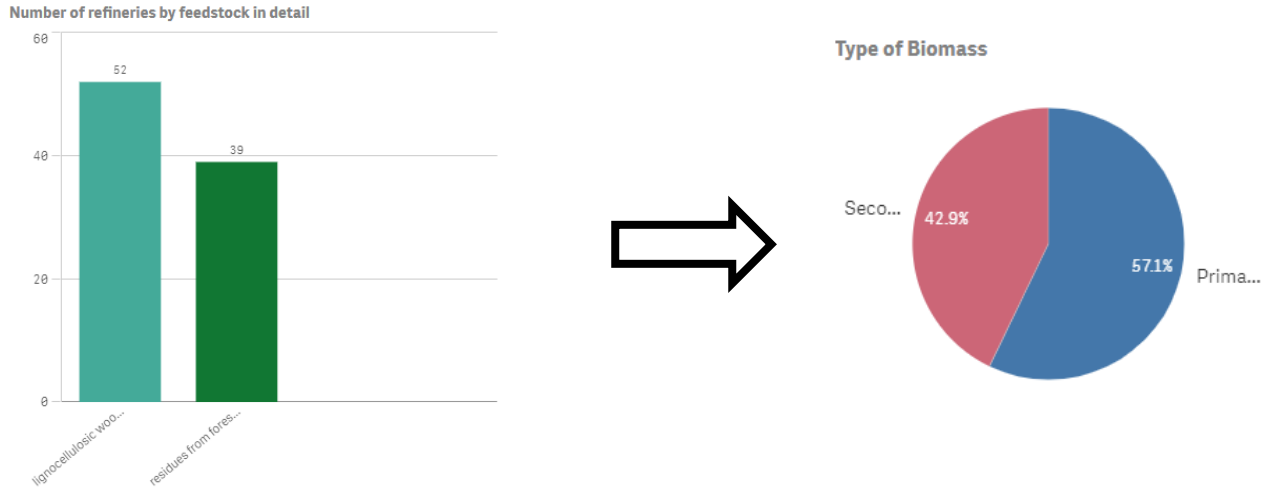


Figure 10. Forestry feedstock category and distribution by type of biomass

[6] This pie-chart, as any other visual element of the dashboard, can also be used to drill down into database. By clicking on either primary or secondary type of biomass of this visualization, the user drills down into the subset of biorefineries using that biomass type.

The pie-chart of Figure 10 shows that 42.9% of the number of detailed forestry feedstock classes are of secondary origin. This 42.9% represents the share of residues from forestry (39) in the total number of detailed feedstock classes (91).

As it has been shown so far, pathways, products and feedstock are the main indicators used in the dashboard and in the database to qualify chemical and material driven biorefineries. The database and the dashboard were designed around these main indicators. The maps of the dashboard allow for a clear visual inspection of the geographical distribution of biorefineries using these indicators. This is useful to uncover spatial patterns of localization and clusters that could help identifying agglomeration economies within the bioeconomy. For example, Belgium and the Netherlands seem to be good examples of MS with a high geographical concentration of chemical and material driven biorefineries with respect to other EU Member States (MS). This seems to be particularly true in terms of chemical driven biorefineries. Such proximity between facilities could be the source of those external economies that spur economic and business growth in the sector locally due to skilled labor force, local suppliers linkages, and knowledge spillovers (Ellison et al., 2010).

Another overview of the geographical distribution of biorefineries across countries together with their composition can be visualized with this dashboard. This overview is provided on the sheet "Countries Data". Here, the distribution of feedstock and product types are presented by country. This representation is useful to easily identify patterns of relative specialization across MS. In fact, each MS is shown in terms of composition of its population of biorefineries both by product and by feedstock classes (either general or detailed). To be noted that in these visualizations, MS have been ordered by number of biorefineries to add an additional dimension to this overview. Figure 11 presents the barcharts for general product and feedstock classes.

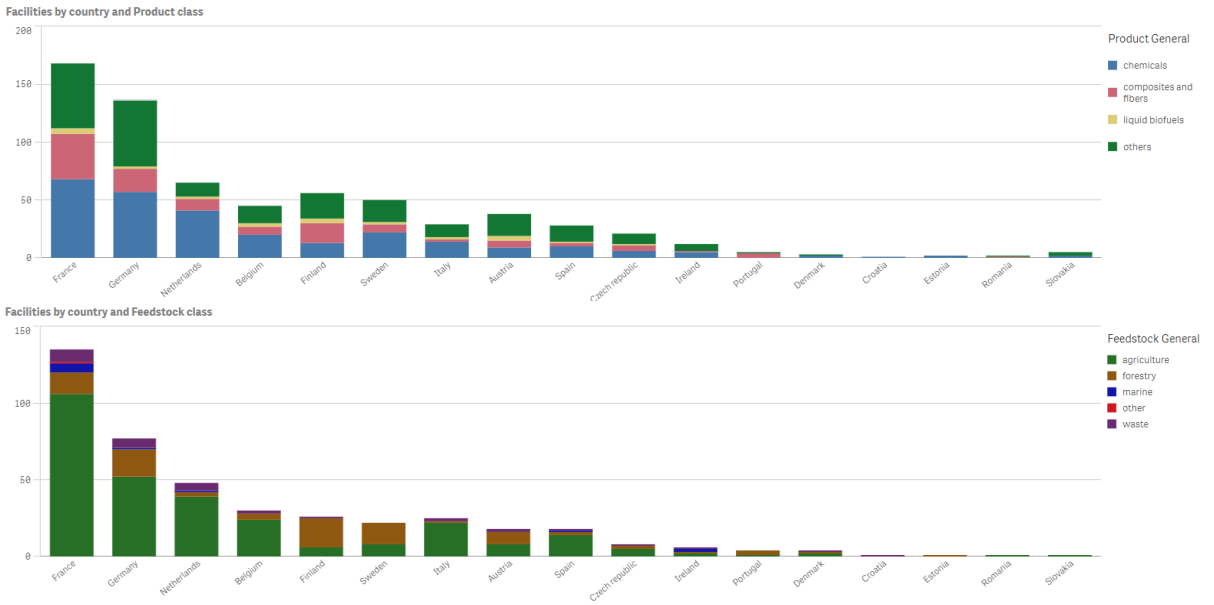


Figure 11. General product and feedstock distribution by MS

Concerning the distribution of product classes, chemicals and other type of products seem to be the dominant classes in the EU. Note that the category "other" is meant to include all those product categories within the scope of the study but that would not fit the available general categories. As already mentioned, examples of these other categories are agrochemicals, feed, pharmaceuticals and other bio-based products. Materials and composites are the third most frequent product class across EU countries. This category seems to be particularly relevant in Finland and Portugal.

In terms of number of biorefineries, France tops the list followed by Germany, the Netherlands, Finland and Sweden. In terms of feedstock classes, the main feedstock type used by chemical and material biorefineries in the EU is coming from agriculture. Agricultural feedstock seems to be particularly relevant in Italy, Spain, the Netherlands and Belgium where it takes a large portion in the total number of feedstock classes. Finland,

Sweden and Portugal seem more specialized in processing feedstock from forestry which is the second most important feedstock type in the EU.

3.2 Value chains

One of the main features of this new database of chemical and material driven biorefineries is its focus on four main structural elements of biorefineries value chains, i.e., feedstock, conversion processes, platform and products. These four elements characterize the production process of biorefineries and can be useful to assess the current state of value chains and their future prospects.

Figure 12 (Platt et al., 2021) shows the schematic representation of value-chains where feedstock is transformed into platforms and intermediate products through a series of conversion processes, and then is converted into final product.

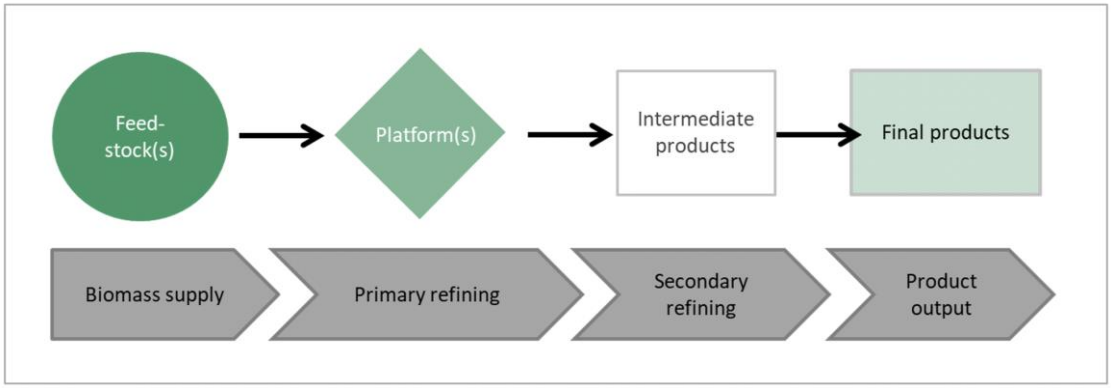


Figure 12. Schematic representation of value chains (Platt et al., 2021)

A representation of these four elements of the value chains is provided in the "Bio Refineries Uses" sheet of the dashboard. Figure 13 gives an overview of this sheet.

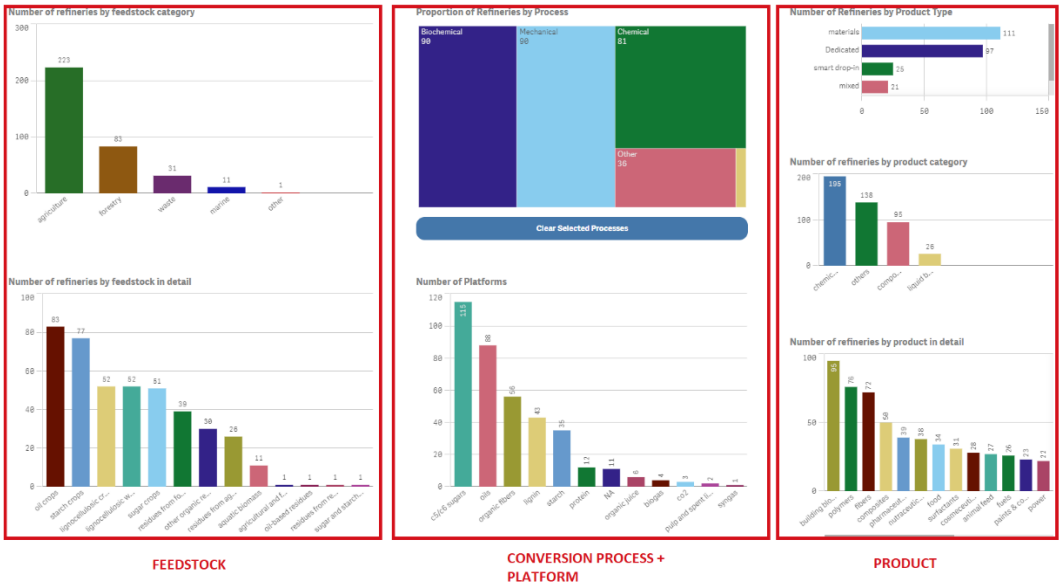


Figure 13. Overview of sheet "Biorefineries uses" with its three main components

This dahsboard sheet is divided horizontally into three main blocks that represent the main steps in the biomass transformation process. On the left-hand side, the distributions of both general and detailed feedstock classes are presented. These distributions are meant to describe the first step in the value chains as presented in Figure 12. At the centre, the distribution of conversion processes and platforms are provided. These central visualizations are meant to capture those various conversion steps and intermediate products that categorize the value chain. Finally, the third block of visualization on the right, presents products classes, both general and detailed, together with the type of product (chemical, material, smart drop-in, dedicated, and mixed). This last set of visualizations is meant to describe the final step of the value chains (Figure 12).

By default, these visualizations present data for the full set of EU biorefineries. So, the full distributions of all feedstock classes, all product classes and all intermediate steps are presented together. Of course, when the full dataset is visualized it may not be easy to identify relations or patterns as many different value chains are represented at the same time. However, the interactivity of the dashboard allows the user to drill down into specific subsets of the database, thus focusing on more specific value chains. Figure 14 shows the updated visualizations after filtering the database by the general feedstock class "forestry".

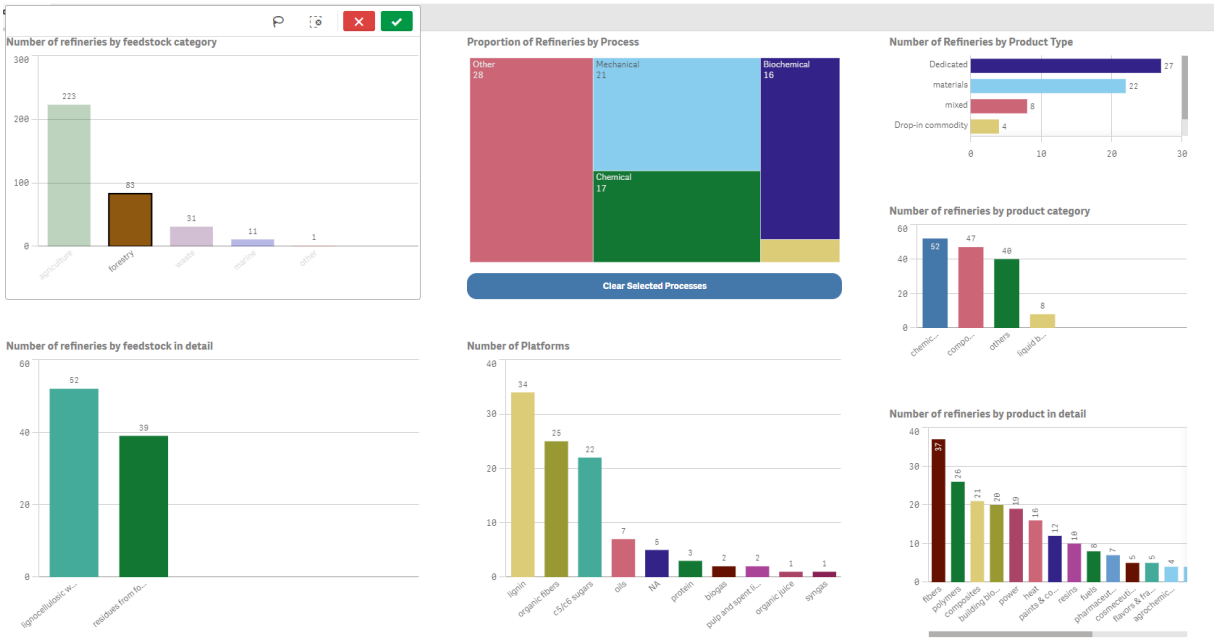


Figure 14. "Bio Refineries Uses" overview of forestry-based value chains in the EU

By choosing forestry as general feedstock category, all the distributions of feedstock types, conversion processes, platform, and products update. First of all, due to the direct link between general and detailed feedstock categories, it is possible to see what the specific categories of feedstock linked to forestry are. As shown in Figure 10, these are lignocellulosic wood/forestry (52) and residues from forestry (39). As already discussed, due to the multi-feedstock nature of biorefineries, the number of specific feedstock categories do not match exactly with the number of general feedstock category (83) because some biorefineries have more than one feedstock category of the same general class.

Associated with the forestry feedstock category there are a number of conversion processes. Among them, other (28), mechanical (21), chemical (17), biochemical (16) and thermochemical (2). These are shown in at the centre of Figure 14. By clicking on any of these conversion processes, the user drills further down into the database. For example, by choosing the mechanical conversion process (Figure 15), the use focuses on the part of the database that is made of those biorefineries that use forestry feedstock and that have a mechanical conversion process.

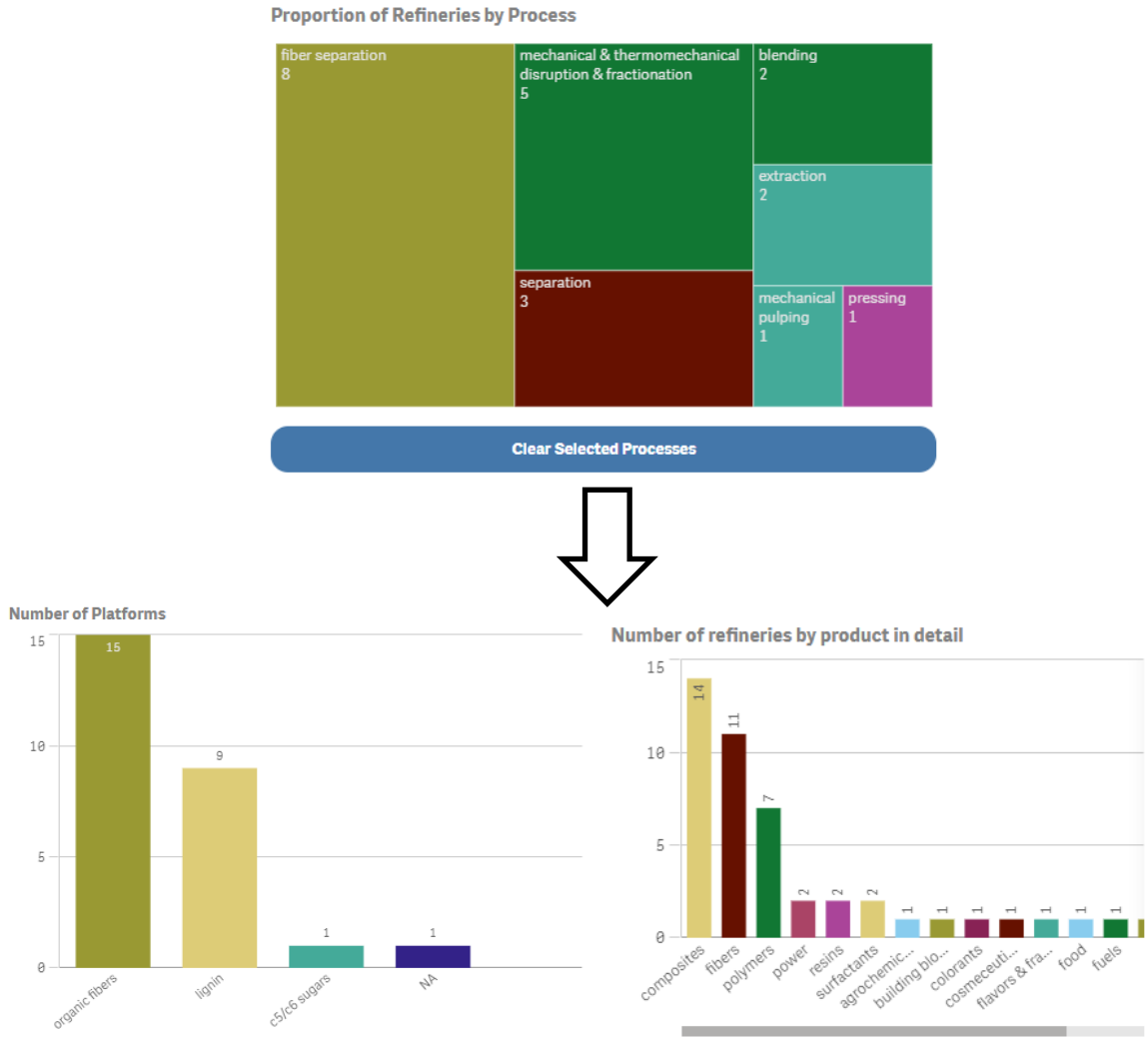


Figure 15. Distribution of platform and detailed products for forestry based biorefineries that use mechanical conversion processes.

Of the mechanical processes, the majority is made of fiber separation (8), mechanical and thermomechanical disruption and fractionation (5), and separation (3). The remaining four conversion processes (blending, extraction, mechanical pulping and pressing) have a lower frequency instead.

In addition to the available mechanical conversion processes, the dashboard presents the distributions of platforms and products for those biorefineries that use forestry feedstock and have a mechanical conversion process. Figure 15 presents these distributions. The distribution of platform shows how the large majority of these biorefineries generate organic fibers and lignin as intermediates. The remaining platform categories (C5/C6 sugars, and NA) are probably categories that are not directly associated to the conversion process of forestry feedstock but that are still generated by the same biorefineries that do. As in the database there may be no direct link between feedstock categories, platforms and products of each of the represented biorefineries, the user should expect some residual categories to be present even in unexpected selections of value chains[7].

[7] The design of a database for biorefineries should take into account the multidimensional nature of their value chains. Every feedstock needs to be associated to its specific conversion process(es), to its corresponding platform(s) and to its corresponding product(s). However, when the biorefinery is a multi-feedstock and multi-product, it is often difficult to be able to link every of these components together due to the lack of publicly available information. The database behind this dashboard represents each biorefinery as a set of feedstock classes, a set of conversion processes, a set of platforms and a set of products classes. These are automatically linked together for single-feedstock and single-product biorefineries, but they are not directly linked with each other for multi-feedstock and multi-product ones. An

The distribution of detailed products shows how composites (14), fibers (11), and polymers (7) are the main products produced by chemical and material driven biorefineries that use forestry as feedstock and that have mechanical conversion processes.

The interactivity of the dashboard allows the user to filter the database from any of the available visualizations, including products. An example of such a filtering is provided in Figure 16 where the selection is made using the general product visualization. After clearing the filter pane and by choosing "chemicals" as general product category, it is possible to see the distributions of feedstock, conversion processes, platform and feedstock associated to those biorefineries that produce chemical products.

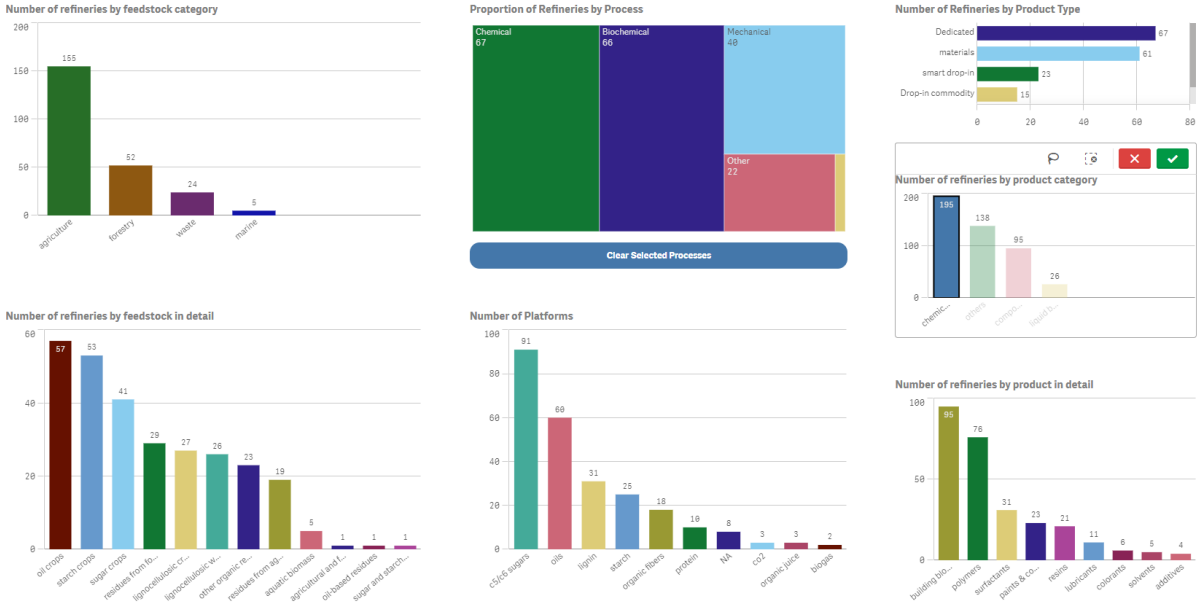


Figure 16. "Biorefineries uses" overview of chemicals-based value chains in the EU

The major feedstock types used by biorefineries producing chemicals is coming from agriculture in the form of oil crops (57), starch crops (53) and sugar crops (41). Therefore, it seems that to a large extent value chains for the production of bio-based chemicals are first-generation value chains. The main conversion processes linked to these value chains are chemical (67), biochemical (66), mechanical (40), other (22) and thermochemical (2). Finally, the major platforms associated with these value chains are C5/C6 sugars (91), oils (60), and lignin (31) and starch (25).

3.3 International comparisons

The database contains data for both EU and non-EU biorefineries. As already mentioned, because of the different coverage level between these two datasets, visualizations are split into two different dashboards. The structure of the two dashboards is the same. Figure 17 presents the first sheet of the dashboard ("Non EU Biorefineries Plants") with the geographical distribution of biorefineries across the selected non-EU countries and their composition in terms of feedstock and products.

attempt to establish a direct link between these elements for all biorefineries was made here by classifying them by pathway.

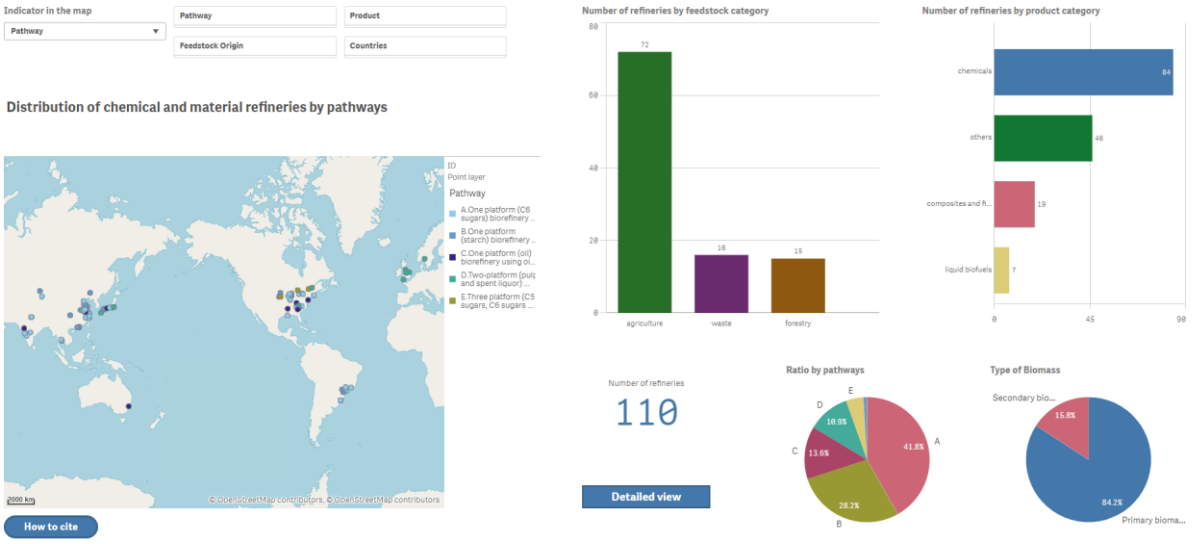


Figure 17. "Biorefineries sheet" of the non-EU dashboard.

The non-EU database contains data on 110 non-EU biorefineries. Unlike EU biorefineries, the majority of these non-EU ones are of pathway A "One platform (C6 sugars) biorefinery using sugar crops" (41.8%). As compared to the EU, commercially available pathways outside the EU make for a significantly larger share (94.5%) of chemical and material driven biorefineries. For what regards the comparison in the use of biomass between EU and non-EU countries, the share of secondary biomass for these non-EU biorefineries (15.8%) is lower than the share of secondary biomass in the EU (22.7%) (Figure 5). The majority of non-EU biorefinery use agricultural feedstock in the form of sugar crops (42), starch crops (37), oils crops (8) and lignocellulosic crops (2) (Figure 18).

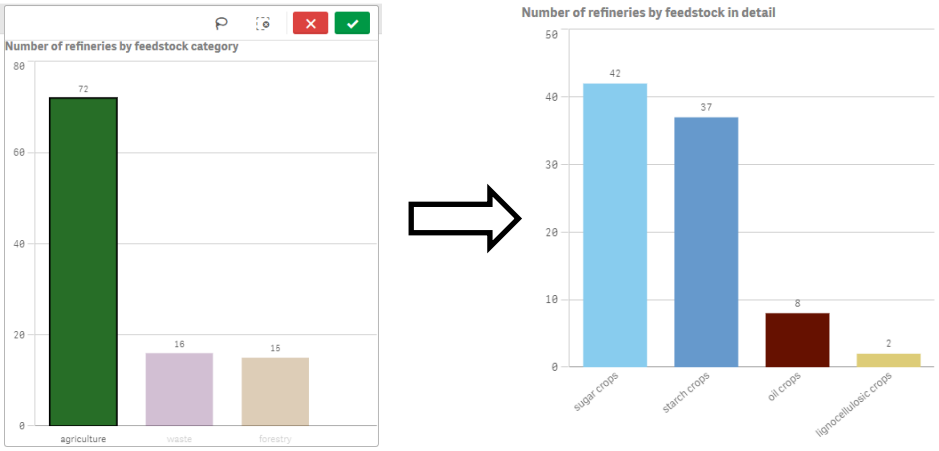


Figure 18. General and detail agricultural feedstock for non-EU biorefineries

A breakdown of the number and composition of biorefineries in non-EU countries is provided in Figure 19. Countries are sorted by number of biorefineries and bars present their distribution in terms of product and feedstock. China has the largest number of refineries followed by USA, and India. Australia and Norway have a very low number of biorefineries (1 each).

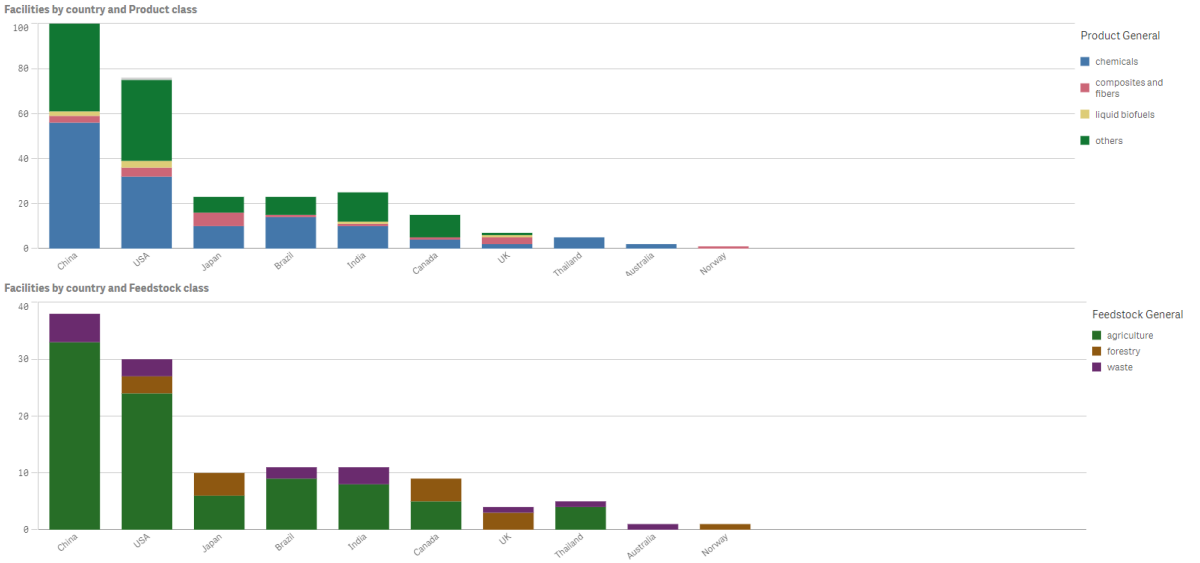


Figure 19. General product and feedstock distribution by country in non-EU countries

Value chains are represented also in the international dashboard. Figure 20 presents the visualizations of the "Bio Refineries uses" sheet for the non-EU biorefineries after applying a filter on the general product category "chemicals".

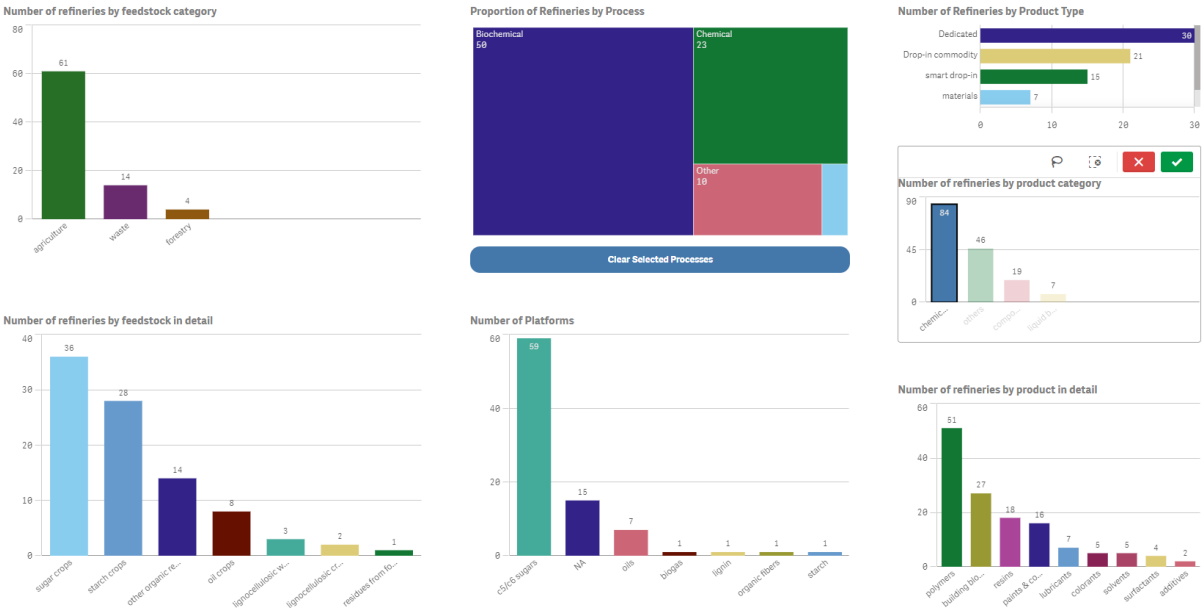


Figure 20. "Biorefineries uses" overview of chemicals-based value chains in non-EU countries

As it was the case for the EU, the major general feedstock type used by biorefineries that produce bio-based chemicals is agriculture. In particular, major detailed agricultural feedstock classes are sugar crops (36) and starch crops (8). In the EU, the single major agricultural feedstock class associated with the production of chemicals was oil crops (57) (Figure 9). This shows that there are major differences in feedstock used inside and outside the EU with possible implications for trade and sustainability. In terms of specific bio-based chemicals produced, like in the EU the two major chemicals produced by biorefineries that produce chemicals outside the EU are polymers, building blocks, resins, and paints and coatings. The major difference between EU

and non-EU chemical products seems to relate to the production of surfactants. In the EU, surfactants take a rather large share (11.4%) of the product categories produced, while surfactants seem to have a more marginal role (2.9%) outside the EU[8].

Given the differences in numbers of biorefineries between EU and non-EU countries, a direct comparison between absolute numbers would be potentially misleading due the different coverage level and representativeness of the two databases. Therefore, such comparisons are not directly carried out in this dashboard. However, the availability of data for EU and non-EU countries is still exploited. Given the limitation of available data, such comparisons are only carried out by looking at the composition of the populations of biorefineries inside and outside the EU. Such comparisons are provided in sheet "Comparisons". This sheet is available in both EU and non-EU dashboards. Figure 21 gives an overview of these comparative visualizations.

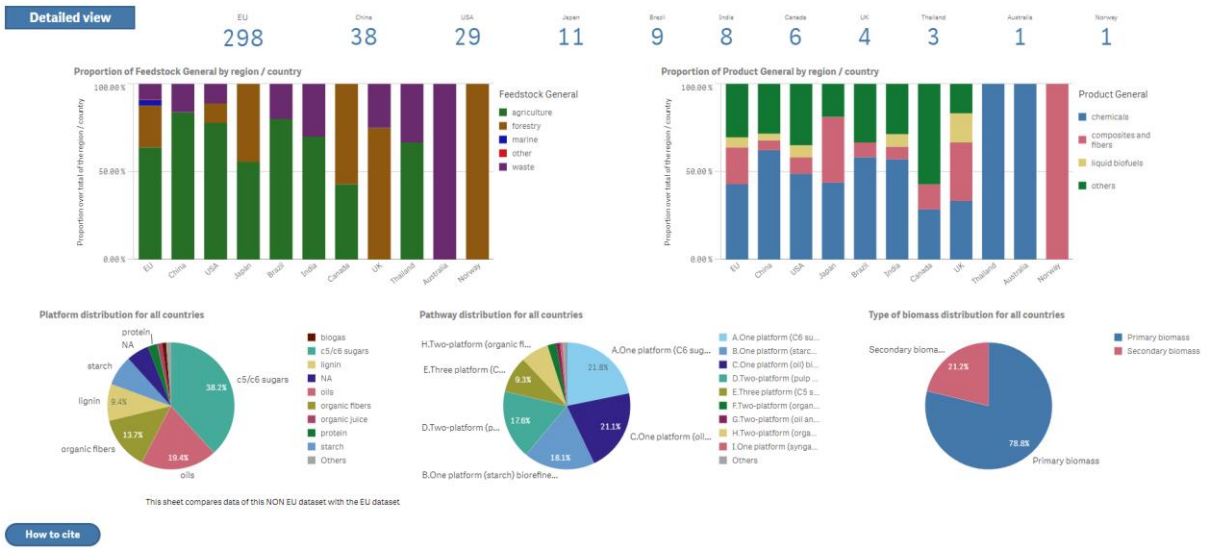


Figure 21. "Comparisons" sheet

This comparative sheet is made of several visual elements. On the top, there are eleven different counters that show the number of selected biorefineries by country (EU is represented as a single block of countries). These counters can be helpful in assessing the representativeness of the comparisons made. In fact, comparisons between countries with very different number of biorefineries may be less reliable.

The next two visualizations provided in Figure 21 are the barcharts that show the composition of each country (or block of countries) in terms of feedstock usage (left) and product produced (right). Just by looking at Figure 21, it is possible to see large differences in the composition of the population of EU biorefineries with respect to non-EU ones. EU biorefineries have a relatively high share of agricultural feedstock (63.9%) and of feedstock coming from forestry (23.8%). China and USA seem to have a rather different feedstock mix instead. Both have a higher share of feedstock of agricultural origin with respect to the EU (83.9% and 77.8% respectively) but China has also a relatively high share of feedstock coming from waste (16.1%) and none coming from forestry. USA has a comparable share of feedstock coming from waste with respect to the EU (11.1% versus 8.9%) but a significantly smaller share of forestry feedstock (11.1%). Thus, it seems that EU biorefineries uses a more diversified feedstock mix with respect to China and USA. The composition of products produced seemed to be more similar across these three major players instead, although the EU seems to be more specialized in composites and materials while China more in chemical production.

As already mentioned, a nice feature of the dashboard is that any single visualization can be used to filter the database and to update all the other visualizations available. This is a very nice feature for inspecting

[8] It should be noted that such result should be taken with case as it could be related to the degree of representativeness of the non-EU database.

relationships at the international level. For example, by selecting a single feedstock from the feedstock barcharts it is possible to see how the dashboard updates. Figure 22 shows the case for forestry feedstock.

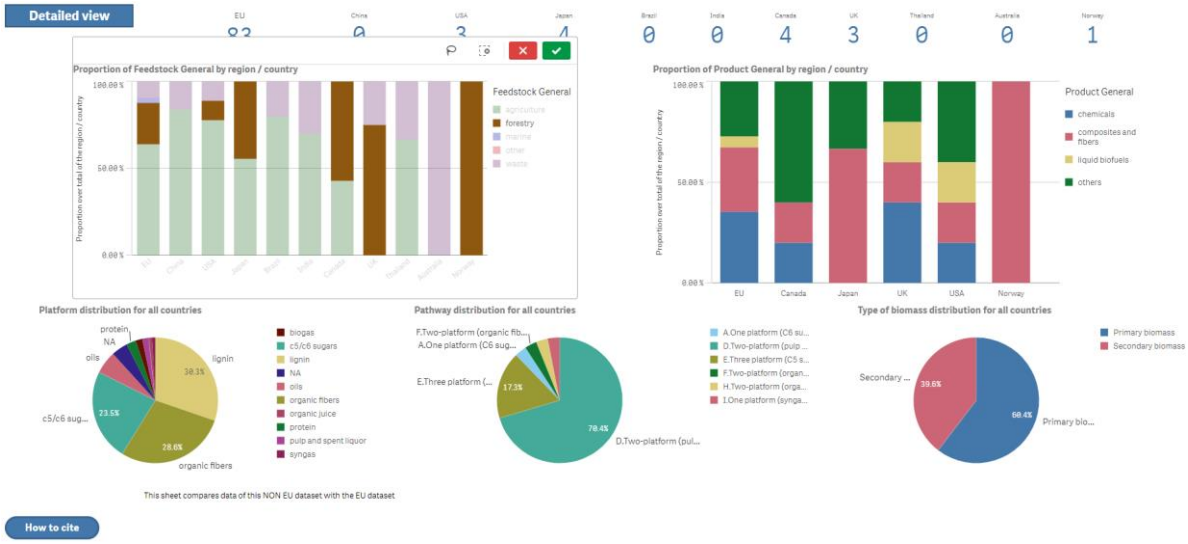


Figure 22. "Comparisons" sheet after filtering for forestry general feedstock

By choosing forestry feedstock among the available general classes, it is possible to highlight the large differences across countries in terms of composition of their population of biorefineries. In fact, not all selected countries use forestry feedstock. The share of biorefineries that use forestry feedstock is large in Japan (44%), Canada (57%), UK (75%) and Norway (100%). However, it should be noted that the number of biorefineries that use forestry feedstock in all the selected non-EU countries is very small (in total 15) if compared to those in the EU (83).

At the bottom of this comparison sheet, three pie charts showing the aggregate distribution of platform, pathway and type of biomass are provided (Figure 22). By choosing forestry as general feedstock category the user drills down into the specific portion of the database and, it can be seen that the distribution of platform changes substantially. For biorefineries that use forestry feedstock, lignin and organic fibers are those two platforms with the stronger presence (30.3% and 28.6% respectively). Then, it can be seen that biorefineries that use forestry feedstock belong for the largest majority (70.4%) to platform D "Two-platform (pulp and spent liquor) biorefinery using woody biomass" and to platform E "Three platform (C5 sugars, c6 sugars and lignin) biorefinery using lignocellulosic biomass". The pie-charts on type of biomass also shows some interesting patterns. In fact, the usage of secondary biomass (39.6%) is much higher for biorefineries that use forestry feedstock than for those that use agricultural feedstock (7.1%). Moreover, a comparison can be made with the share of secondary biomass in the forestry sector in the EU and outside the EU. Figure 10 showed that the share of these secondary feedstock in the EU was 42.9% while Figure 22 shows that the share of secondary feedstock inside and outside the EU is 39.6%. This may point to the fact that the non-EU part of the population of chemical and material biorefineries is more reliant on primary feedstock types that those in the EU.

4 Final observations

The present database and its dashboards provide an overview of the current state of chemical and material driven biorefineries, both on EU level and for ten selected countries outside the EU.

With regard to the EU's Updated Bioeconomy Strategy and its action plan to build an efficient and sustainable bioeconomy, the present database and documentation shows that the EU has a good basis to strengthen and scale-up the bio-based sector (tier 1 of the action plan). It is clear that an action plan conceived at the end of 2018 cannot result in new operational (chemical and material) biorefineries three years later, given the complexity and long-term investments for a biorefinery. The importance of building-up infrastructure for the bioeconomy has been also stressed in the IACGB Communiqué from 2020, stating that "Bioeconomy development requires investments in research and development infrastructure, but also bridging the gap between demonstration and industrialization with the help of large-scale biorefinery development" (https://gbs2020.net/wp-content/uploads/2020/11/GBS2020_IACGB-Communique.pdf).

The following observations can be drawn from the database:

1. There are many chemical and material driven biorefineries operational inside (298) (and outside of) the EU, producing a multitude of different products.
2. The majority of these biorefineries belong to a commercially viable pathway (A-D) both in the EU and outside the EU. The share of still-non-commercially viable pathways (E-K) is marginal.
3. In the EU, the major pathway is represented by pathway C "One Platform (oil) biorefinery using oil crops, wastes and residues".
4. In the EU, chemical production is geographically concentrated in the Netherlands and Belgium. Other product categories such as composites and fibres and other types of products are less geographically concentrated in the EU.
5. Major detailed chemical products produced in the EU are building blocks, polymers and surfactants.
6. The major feedstock used by chemicals and material driven biorefineries is represented still by primary agricultural feedstock. Of major relevance in the EU is the use of oil crops and starch crops.
7. The use of forestry feedstock is associated with larger use of secondary types of biomass (in the EU 42.9% versus an aggregate share of 22.7%).
8. Of the 110 non-EU biorefineries identified, the majority are located in China (38) and in the USA (29).
9. Outside the EU the major pathway is represented by pathway A "One platform (C6 sugars) biorefinery using sugar crops".
10. It seems that EU biorefineries use a more diversified feedstock mix with respect to China and USA with agricultural feedstock being the most prominent type of feedstock used across countries.
11. The composition of products produced seems to be more similar across EU, China and USA, although the EU seems to be more specialized in composites and materials while China in chemical production.
12. In terms of types of biomass, in the EU the share of secondary biomass (22.7%) seems to be higher than that outside the EU (15.8%).

Additional data and insights can be found in Platt et al. (2021). The reader and user of the database and its dashboards should note that due to the lack of data on the production volumes and capacity, no estimations of the importance of the analysed biorefineries as regards the total production in the EU can be performed. Furthermore, the database does not provide direct information on the environmental performance.

The JRC and its partners are planning to make future updates of the map of biorefineries and bio-based facilities, depending on policy needs and available resources. In this respect, users of the online platform are welcome to inform the JRC (through the email address JRC-DATAM@ec.europa.eu) in case they identify wrong or missing information in the list or classification of bio-based facilities.

Users of the dashboards and its data are asked to reference according to the "how to cite" buttons in the dashboards and, in the case of quotations of the present report, follow the instruction on page 2.

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A. Annex I – RoadToBio Top 120 chemicals uses for database

Chemical	Classification
Acetaldehyde	drop-in commodity
Acetic acid	smart drop-in
Acetic anhydride	smart drop-in
Poly(vinyl chloride) - PVC	drop-in commodity
Acetone	drop-in commodity
Alkanes (iso-)	drop-in commodity
Alkyl polyglucosides (APG)	dedicated chemical
Azelaic acid (aka nonanedioic acid)	dedicated chemical
Bio-'Naphtha'	drop-in commodity
Butadiene	drop-in commodity
Butanediol (1,2-)	smart drop-in
Butanediol (2,3-)	smart drop-in
Butanol (iso-)	drop-in commodity
Butanol (n-)	drop-in commodity
Sorbitan	dedicated chemical
Capric acid (aka decanoic acid)	dedicated chemical
Poly(tetrahydrofuran) - PTHF (aka PTMEG)	smart drop-in
Caproic acid (aka hexanoic acid)	dedicated chemical
Caprylic acid (aka octanoic acid)	dedicated chemical
Carboxymethyl cellulose	dedicated chemical
Cellulose	dedicated chemical
Phenol formaldehyde resin	smart drop-in
Cetylic alcohol	dedicated chemical
Chitin/Chitosan	dedicated chemical
Citric acid	dedicated chemical
Dimethyl isosorbide	dedicated chemical
Docosahexaenoic acid	dedicated chemical
Epichlorohydrin	smart drop-in
Epoxy resins	smart drop-in
Esterquats (group	dedicated chemical
Ethanol	smart drop-in
Ethyl acetate	drop-in commodity
Ethyl lactate	dedicated chemical
Ethyl tert-butyl ether (ETBE)	drop-in commodity
Butene (iso-)	drop-in commodity
Ethylene	drop-in commodity
Isoprene	drop-in commodity

Farnesene	dedicated chemical
Ethylene glycol	drop-in commodity
Fatty Alcohols	dedicated chemical
Fatty amines	dedicated chemical
Furfural	dedicated chemical
Ethylene chloride (aka vinyl chloride)	drop-in commodity
Furfuryl alcohol	dedicated chemical
Glucaric acid / Sodium glucarate	dedicated chemical
Glycerol	dedicated chemical
Heptanoic acid (aka enanthic acid)	dedicated chemical
Heptanol	smart drop-in
Hyaluronic acid	dedicated chemical
Isosorbide	dedicated chemical
Itaconic acid	dedicated chemical
Lactic acid	dedicated chemical
Lactide	dedicated chemical
Lauric acid (aka dodecanoic acid)	dedicated chemical
Butanediol (1,4-)	smart drop-in
Lauryl alcohol	dedicated chemical
Limonene	dedicated chemical
Dodecanedioic acid	dedicated chemical
Methane	drop-in commodity
Methanol	drop-in commodity
Methyl tert-butyl ether (MTBE)	drop-in commodity
Octadecanedioic acid (1,18-)	dedicated chemical
Octanol (2-)	dedicated chemical
Oleic acid	dedicated chemical
Palmitic acid (aka hexadecanoic acid)	dedicated chemical
Pelargonic acid (aka nonanoic acid)	dedicated chemical
Poly(butylene adipate-co-terephthalate) - PBAT	smart drop-in
Poly(butylene succinate) - PBS (aka 'Bionolle')	smart drop-in
Butyric acid	smart drop-in
Poly(butylene terephthalate) - PBT	drop-in commodity
Poly(ethylene furanoate) - PEF	dedicated chemical
Poly(ethylene glycol) - PEG	drop-in commodity
Poly(ethylene terephthalate) - PET	drop-in commodity
Poly(ethylene) - PE	drop-in commodity
Acrylic acid	smart drop-in
Methyl methacrylate (MMA)	smart drop-in
Poly(hydroxyalkanoate) - PHA	dedicated chemical
Poly(hydroxybutyrate) - PHB	smart drop-in
Poly(isosorbide)	dedicated chemical
Fumaric acid	smart drop-in

Poly(lactic acid) - PLA	dedicated chemical
Malic acid	smart drop-in
Poly(methyl methacrylate) - PMMA	smart drop-in
Adipic acid	smart drop-in
Poly(propiolactone) - PPL	dedicated chemical
Poly(propylene) - PP	drop-in commodity
Levulinic acid	dedicated chemical
Poly(trimethylene terephthalate) - PTT	drop-in commodity
Poly(urethane) - PUR	drop-in commodity
Hydroxypropionic acid (3-)	dedicated chemical
Propane	drop-in commodity
Propanediol (1,3-)	smart drop-in
Acrylonitrile	drop-in commodity
Propylene	drop-in commodity
Propylene glycol (aka 1,2-propanediol)	drop-in commodity
Tetrahydrofuran (THF)	smart drop-in
Hydroxymethylfurfural (5-) (HMF)	dedicated chemical
Furandicarboxylic acid (2,5-) (FDCA)	dedicated chemical
Furan	dedicated chemical
Tetrahydrofuran (methyl-)	smart drop-in
Rayon	dedicated chemical
Ricinoleic acid (aka 12-Hydroxyoctadec-9-enoic acid)	dedicated chemical
Dimethyl ether (DME)	drop-in commodity
Sebacic acid (aka decanedioic acid)	dedicated chemical
Sophorolipids	dedicated chemical
Ethylene oxide	drop-in commodity
Propylene oxide	drop-in commodity
Sorbitol	dedicated chemical
Squalene	dedicated chemical
Starch	dedicated chemical
Stearic acid (aka octadecanoic acid)	dedicated chemical
Guayule	dedicated chemical
Glycolipids	dedicated chemical
Succinic acid	smart drop-in
Glycerol carbonate	dedicated chemical
Terpenes	dedicated chemical
Turpentine (mixture --> pinene)	dedicated chemical
Undecanoic acid (aka undecylic acid)	dedicated chemical
Alkyl polypentosides (C5 surfactants)	dedicated chemical
Xylene (para-)	drop-in commodity

B. Annex II – List of keywords for material biorefineries

1 Absorbents
2 accessories
3 active
4 Actives
5 additive
6 adhesive
7 adsorbent
8 agent
9 alcohol
10 aroma
11 aromatherapy
12 automotive products
13 biodegradable
14 blend
15 cable
16 care product
17 cellulose
18 cellulosic material
19 Chemical intermediates
20 cleaner
21 cleaners
22 cleaning products
23 Coating
24 component
25 Composite
26 compound
27 compounding
28 container
29 cosmetics
30 de-icer
31 detergent
32 dye
33 elastomer
34 emollient
35 emulsion
36 enzyme
37 equipment
38 extract
39 fabric
40 feedstock
41 fertilizer
42 Fibre
43 fill and batt
44 film
45 filter
46 floor
47 floor panel
48 foam
49 gel
50 grease
51 herbicide
52 ink
53 Insulation
54 Insulator
55 intermediate
56 lining

57 material
58 medical
59 oil
60 packaging
61 Paint
62 panel
63 paper
64 personal care ingredient
65 personal hygiene products
66 pharmaceutical
67 plastisizer
68 polymer
69 protection
70 relief
71 repellent
72 resin
73 roofing
74 roving
75 Rovings, yarns
76 sanitary product
77 sealant
78 soap
79 solvent
80 stain
81 surfactant
82 Textile
83 Thermoplastic
84 tires
85 tissue
86 toiletry
87 treatment
88 Treatment products
89 varnish
90 Vitamin
91 wax
92 wire
93 yarn

On-line resources

An interactive dashboard presenting this report's main results is available on the public website "JRC agro-economic portal DataM". Links can be also accessed with the below QR codes.

Figure A1. QR code – DataM URL

https://datam.jrc.ec.europa.eu

Source: JRC, 2021.

Using DataM users can access and analyse main results of the report through an interactive dashboard.

Figure A2. QR code – Chemical and material biorefineries in the EU URL

https://datam.jrc.ec.europa.eu/datam/mashup/CHEMICAL_BIOREFINERIES_EU/index.html

Source: JRC, 2021.

Figure A3. QR code – Chemical and material biorefineries in non-EU countries URL

https://datam.jrc.ec.europa.eu/datam/mashup/CHEMICAL_BIOREFINERIES_NON_EU/index.html

Source: JRC, 2021.

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