Project Title: Roadmap for the Chemical Industry in Europe towards a Bioeconomy

Acronym: RoadToBio

Grant Agreement No: 745623

Start Date: 01 May 2017

Duration of the Project: 24 Months

Deliverable No.	*D2.5*
Deliverable Title	*Concept of bio-based and circular economy*
Type	*Report*
Due Date	*15 February 2019*
Date Delivered	*15 February 2019*
Prepared by (Lead Partner)	*Christopher vom Berg (lead author) and Lara Dammer - nova-Institut für politische und ökologische Innovation GmbH* *Swinda Pfau and John Vos – BTG Biomass Technology Group B.V.*
Dissemination Level	*Public*

This project has received funding from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 745623.

Table of Contents

Acronyms and Abbreviations

Acronyms and Abbreviations:

Short name	Full name
AHP	Absorbent hygiene products
BBI JU	Bio-based Industries Joint Undertaking
BIC	Bio-based Industries Consortium
BTG	Biomass Technology Group B.V.
CO_2	Carbon dioxide
CRM	Critical Raw Materials
DECHEMA	Gesellschaft für chemische Technik und Biotechnologie e.V. (Society for Chemical Engineering and Biotechnology)
E4tech	E4tech (UK) Ltd.
EC	European Commission
EU	European Union
nova	nova-Institut für politische und ökologische Innovation GmbH
OECD	Organisation for Economic Cooperation and Development
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
RoadToBio	Roadmap for the Chemical Industry in Europe towards a Bioeconomy (Project Acronym)

1. Executive Publishable Summary

A number of aspects relevant for the bio-based economy also touch on the circular economy. This report summarizes existing literature on possible interfaces between bio-based and circular economy, but also points out relevant differences between the goals of the concepts.

In context of the RoadToBio project, a closer look is taken on several fields of the chemical industry. The report introduces a number of selected topics from within the chemical industry, that in some way correlate, align with the circular economy or cause particular issues. The presented examples are in no way exhaustive, but they provide a good indication about the bandwidth and importance of the chemical industry within the bio-based and circular economy concepts. The relevant topics that were more closely investigated are:

1. Bio-based plastics and its recycling
2. Oleochemistry
3. Utilisation of Waste / side streams
4. Biodegradability of chemicals
5. Ecodesign
6. Biorefineries
7. Critical raw materials
8. Chemical recycling
9. CO_2 utilisation

In conclusion, the concept of the bio-based economy and the circular economy have similar targets and are overlapping to a larger extent, but neither is fully part of the other. In other words: the circular economy is not complete without the bio-based economy and vice versa. The intersection between the two concepts is called the “circular bioeconomy” and there are clear intersections to be identified and advantages to be gained by aligning the two concepts.

In the future, our fossil-based economy will have to evolve towards a renewable resource base, and an aligned approach of both the bio-based and the circular economy can play an important part in that development. In this transformation, the chemical industry can play an important part, as it is a key player for both the bio-based and the circular economy and can be incremental for innovation and further development of a combined, sustainable concept.

2. The bio-based economy and the circular economy

A number of aspects relevant for the bio-based economy also touch on the circular economy. This report therefore identifies possible interfaces between bio-based and circular economy, but also points out relevant differences between the goals of the concepts. In context of the RoadToBio project, a closer look is taken on several fields of the chemical industry, how the respective fields fit into the bio-based and the circular economy and whether there are already existing or potential fields of alignment. This way, the report develops a concept of how the bio-based economy as a whole, and the chemical sector especially, will fit into the circular economy.

2.1 The bio-based economy

The bio-based economy is defined in different ways around the world. Shared by most of its definitions is the understanding of “bioeconomy as the knowledge-based production and utilisation of biological resources, innovative processes and principles to sustainably provide goods and services across all economic sectors” (GBS 2015). Often, the terms bio-based economy and bio-based economy are used congruently, sometimes they are further differentiated. In those cases, the bio-based economy only involves the sectors of bio-based materials, bio-based products and bioenergy.

In 2012, the European Commission (EC) published their bioeconomy strategy document *Innovating for sustainable growth: a bioeconomy for Europe*, which provided a framework to stimulate knowledge development, research and innovation on the conversion of renewable biological resources into products and energy. Here the EC defines that “the bioeconomy encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy” (EC 2012).

For an effective bio-based economy, large quantities of biomass must be mobilised from a variety of resources: Biomass can come from agriculture, from forestry, from marine resources, but also from waste fractions of all these environments as well as from consumer markets like food waste. Unlike fossil resources, biomass regrows in a relatively short period of time. This way utilisation of raw materials taken from the planet can be compensated. A bio-based economy can thus contribute to creating a sustainable economy. Consequently, a major objective of the bio-based economy is an increasing replacement of fossil-based production with bio-based alternatives (Philp and Winickoff 2018). Further below, we will illustrate that bio-based economy can provide several more benefits to society related to this overarching objective (cf. Figure 3).

2.2 The circular economy

The circular economy aims to avoid all waste, instead using materials in a circular fashion where nothing is lost but feeds into new cycles. It looks beyond the linear “take-make-dispose” model and replaces it by a model where materials and products and their value are preserved for as long as possible, and where the generation of waste and pollution are minimised or even removed. Instead, materials and products are reused and recycled as long as possible, or ideally even indefinitely. Systemic approaches, including ecodesign, sharing, reusing, repairing, refurbishing and recycling of existing materials and products, play a significant role in maintaining the utilisation of components and materials, and retaining their value (Reichel et al. 2016).

A well-known depiction of the circular economy is the butterfly diagram of the Ellen MacArthur Foundation (Figure 1), which splits the economy into continuous flows of technical and biological materials through the "value circle".

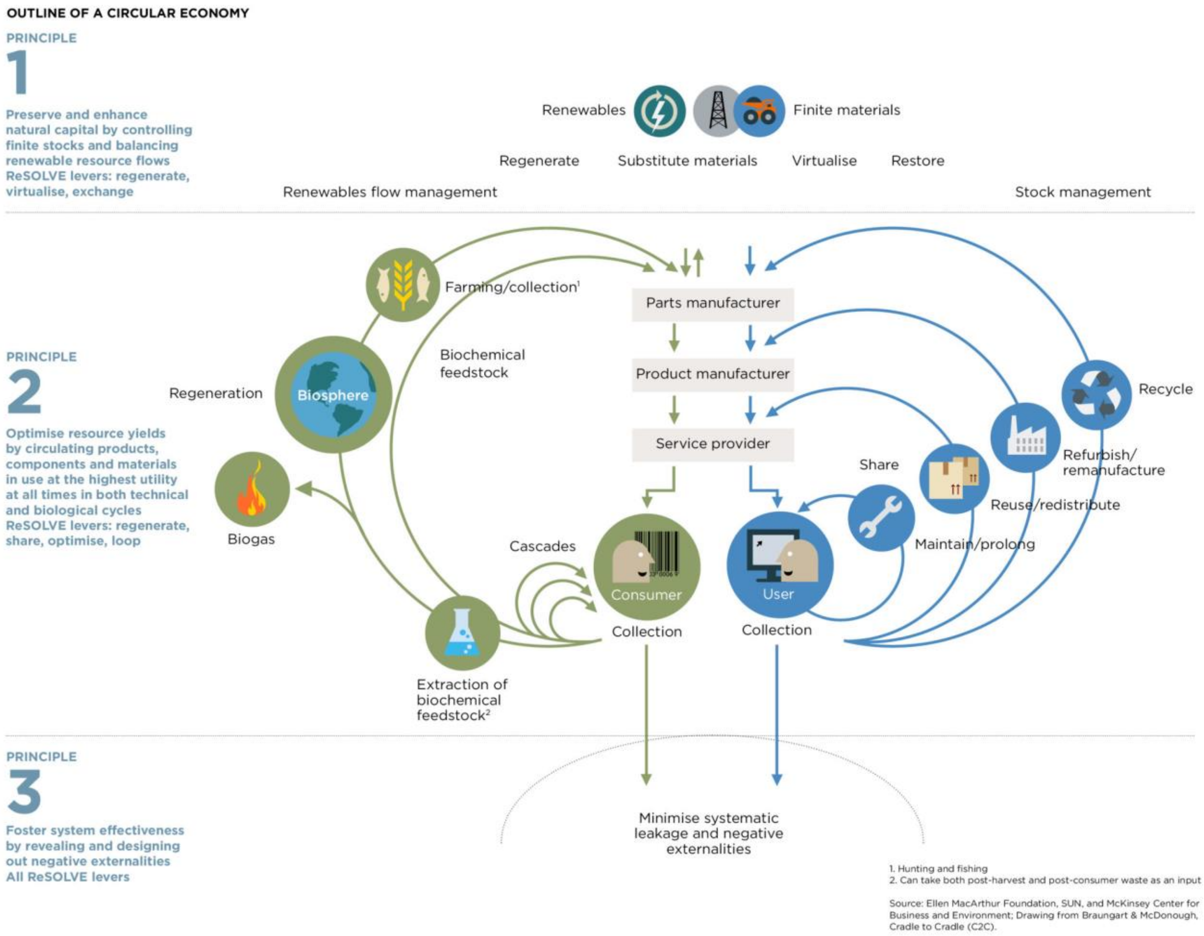

Figure 1: Circular Economy System or "Butterfly" Diagram from the Ellen MacArthur Foundation

In 2017, nova-Institute published a further developed, alternative illustration of material flows in the circular economy (Figure 2), with the main intention to avoid the differentiation into the technical and biological cycles: Many bio-based products actually enter the technical cycle as well and are getting reused, recycled or similar, and only a smaller fraction enters the biological cycle. In a recent report, researchers of the Swedish Environmental Research Institute (Harris et al. 2018) argue that "*when addressing renewable (bio-based) materials it* [the circular economy definition of the Ellen MacArthur Foundation] *places a strong emphasis on their biodegradability. In doing so it tends to overlook the contribution that renewable feedstock and reuse and recycling of renewable materials can have on improving circularity and environmental performance.*"

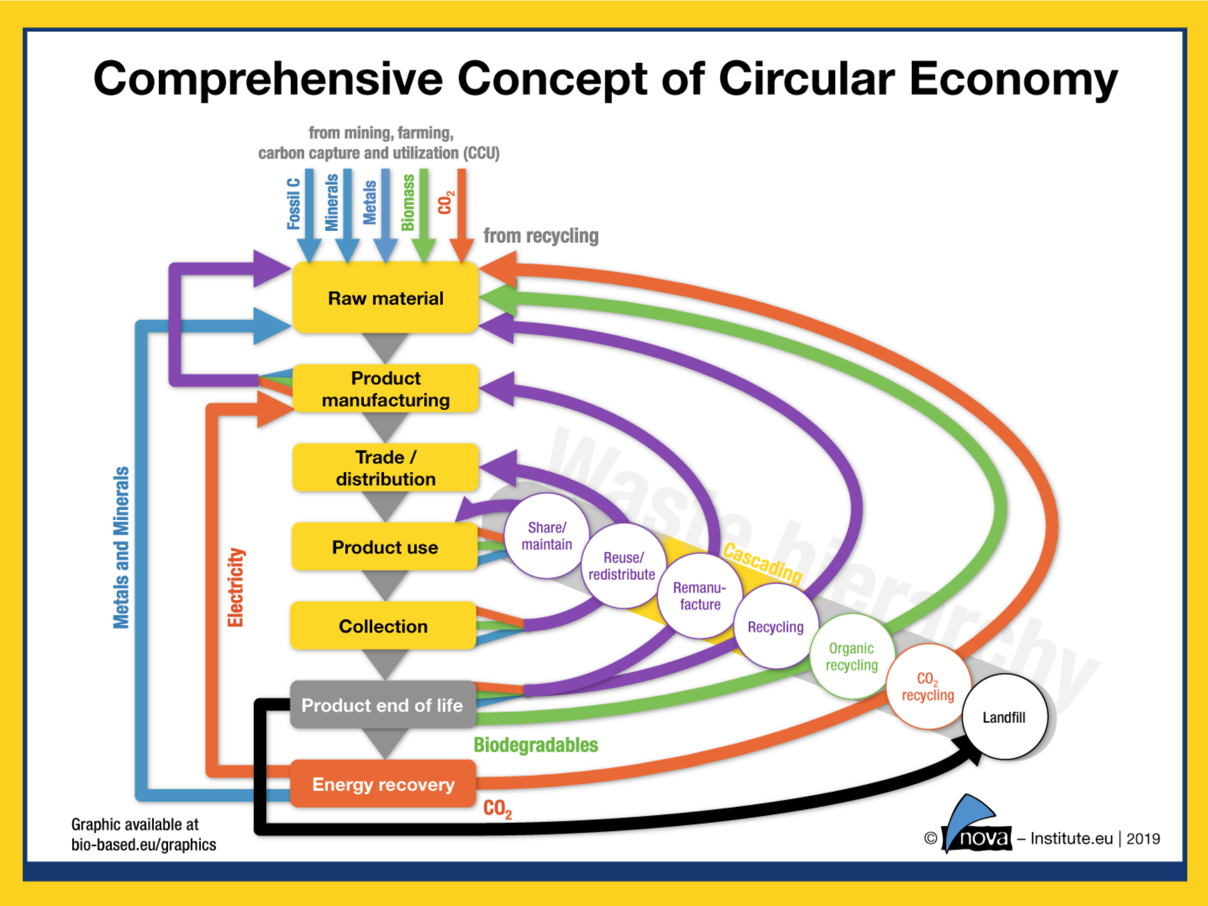

Figure 2: Comprehensive Concept of Circular Economy – 'Biomass' includes all kinds of biological resources, from agriculture, forestry and marine environments as well as organic recycling (Carus 2017)

In Figure 2, material streams and their different utilisation routes belonging to a circular economy are depicted, including organic recycling (=biodegradation) and the capture and utilisation of CO_2. At the top, there are all kinds of raw materials entering the cycle: Fossil resources (crude oil, natural gas, coal), minerals, metals, biomass from agriculture, forest and marine environments and potentially CO_2. In regards to the bio-based economy, biomass as a raw material is used for a wide range of applications, which include food, feed, bioenergy and all kind of bio-based materials and products.

The raw materials will be manufactured to products, traded, used and then will enter the waste hierarchy from share/maintain, reuse/redistribute, remanufacture to recycling (mechanical and chemical). This hierarchy covers most of the bio-based products. Biodegradable products allow for organic recycling as an additional end-of-life option. The figure shows that most bio-based products are potentially part of the circular economy; those parts usually called "cascading" are represented through the remanufacturing and recycling stages.

2.3 Interfaces between the bio-based economy and the circular economy

In its 2015 Circular Economy Action Plan, the European Commission includes two sectorial priorities that are directly linked to the bio-based economy: food waste and the efficient conversion of biomass (EC 2015). There are a number of interfaces and links between the

2015 Circular Economy Action Plan[1] and the 2012 Bioeconomy Strategy[2]. Both identify food waste, biomass and bio-based products as areas of intervention and both follow similar guidelines, such as sustainability and a lower GHG footprint, increased resource efficiency, cascading use of biomass, valorisation of waste and side streams, tackling fossil production and consumption, and considering the global dimension (De Schoenmakere et al. 2018).

Utilisation of biomass as a resource is a key interface between the bio-based economy and circular economy. In light of heated debates about whether food crops should be used for purposes other than food supply, non-food sources of biomass have been explored and are further investigated. This includes many biomass sources that are considered "**by-products**", "**residues**" or "**wastes**" **–** Examples are agricultural or forestry residues and municipal solid waste or food waste. Here, a large interface with the circular economy concept can be identified for several reasons (Philp and Winickoff 2018):

- Using biomass residues/wastes keeps materials in the economy for longer
- Using biomass residues/wastes closes material loops
- Using biomass residues/wastes increases resource productivity

Another strong overlap between the bio-based and the circular economy can be identified in the **cascading use** of biomass. The term cascading refers to sequential recycling of a material into another type of product at its end of life. The main target of both cascading use and the circular economy is an increased resource efficiency and less demand for fresh materials, with both of these frequently linked to added value and job creation. Cascading is therefore a fundamental component of the circular economy and conscious cascading also contributes to increased resource efficiency in the whole system. In some bio-based sectors, cascading use has already been established for decades, many years before the term "circular economy" became mainstream. Examples are the pulp and paper or textile industries (Carus 2017).

An overarching goal of both the bio-based economy and circular economy concepts is that they strive to create a **more sustainable and resource efficient world** with a lower carbon footprint. In this regard, both avoid using additional fossil carbon to contribute to climate targets: The circular economy improves resource efficiency and the use of recycled materials to reduce the need of additional fossil carbon, the bio-based economy substitutes fossil carbon by renewable carbon from biomass (Carus 2017). Both concepts have their challenges to align robustly with sustainability, but they can provide valuable lessons to each other: A central message for the circular economy is that sustainability can be increased through utilisation of renewables in the technical cycle, e.g. reducing the climate change impacts (Harris et al. 2018).

2.4 Differences between the bio-based economy and the circular economy

Besides the mentioned interfaces, the bio-based economy and circular economy also differ from each other in a number of aspects. The main conclusions from literature are:

1) Most of the currently existing material flows are not part of the circular economy, largely because the tools for cascading use, recycling and circulating are not sufficiently developed yet. This is true for many material-based economies, e.g. fossil

[1] including the 2018 Circular Economy Policy Package
[2] including the updated Bioeconomy Strategy 2018

carbon, most metals and minerals, and also for the bio-based economy, but in the future the circular economy has the potential to become large-scale.

2) Some areas of the bio-based economy can never fully become part of the circular economy because their applications are impossible to reuse or recycle. Examples are (for now) bio-based fuels and incineration of biomass for energy generation, but also many cosmetics or paints and coatings, which cannot be properly collected and recycled due to their nature of application.
3) The main targets of the bio-based and the circular economy concepts overlap, but are not entirely the same: The bio-based economy has a much wider scope beyond circularity and increased resource efficiency, as it also includes innovation in agriculture and forestry, novel and less toxic/harmful pathways by the application of biotechnological processing steps, new chemical building blocks, properties, functionalities.
4) The Circular Economy Action Plan mentions biomass and biomaterials as a priority, but a wholistic approach to their sustainable application, including biodiversity aspects, nutrient cycles and the time-dimension of bio-based cycles (e.g. biodegradability) is lacking (De Schoenmakere et al. 2018).

For a proper alignment of the bio-based economy and the circular economy, it is important to treat both as independent entities to avoid omitting certain crucial aspects which do not overlap. Figure 3 maps the bio-based economy and shows its interfaces to the circular economy (blue boxes), but also highlights unconnected fields. In conclusion, the bio-based economy and its research agenda, strategy, and policy do overlap with a circular economy strategy, but will always need additional and specific topics (Carus and Dammer 2018).

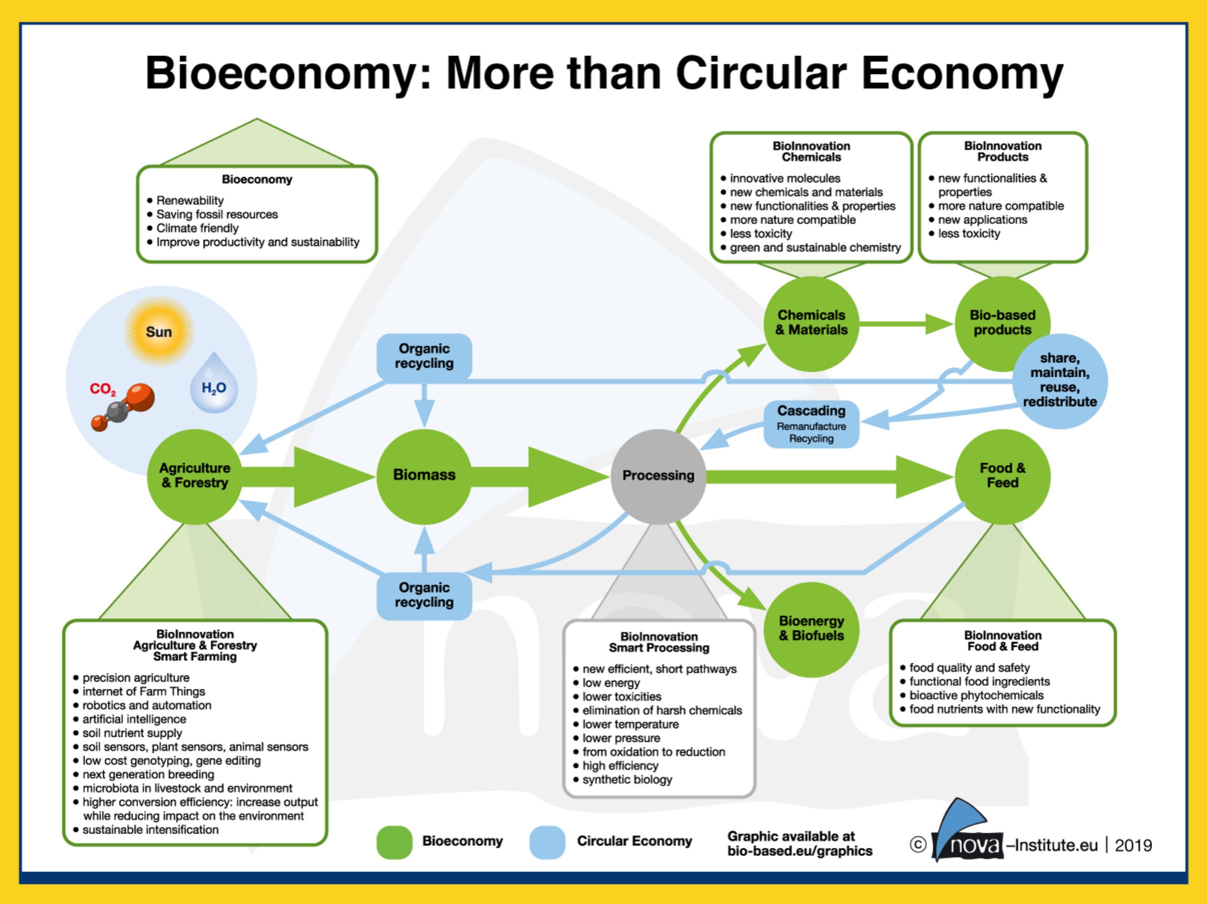

Figure 3: Bioeconomy beyond circular economy. "Agriculture & Forestry" includes all kinds of biomass, from agriculture, forestry and marine as well as organic waste streams.

3. A closer look at the bio-based chemical industry and the circular economy

For the RoadToBio project, the chemical industry is in the focus of all investigations. While we have introduced a more general view on the interface between the bio-based economy and the circular economy, in the following we are going to focus on the chemical industry.

An important notion for the chemical industry is that it only may develop into a sustainable sector once it phases out fossil raw materials and utilises nothing but renewable and recycled carbon as a raw material. Unlike the reasonably called for decarbonization of the energy sector, the organic chemistry per se cannot be decarbonised – on the contrary it is entirely based on the use of carbon. The chemical industry processes can of course be optimised and decarbonised in terms of energy usage, but the equivalent to decarbonization in the energy sector is a transition to carbon from renewable sources for the organic chemistry. Currently, the only available sources for renewable and recycled carbon are recycling, biomass and direct CO_2 usage (Carus and Raschka 2018).

In the following, this report introduces a number of selected topics from within the chemical industry, that in some way correlate, align with the circular economy or cause particular issues. The presented examples are in no way exhaustive, but they provide a good indicator about the bandwidth and importance of the chemical industry within the circular economy. In the next segments, the following topics are discussed:

10. Bio-based plastics and its recycling
11. Oleochemistry
12. Utilisation of Waste / side streams
13. Biodegradability of chemicals
14. Ecodesign
15. Biorefineries
16. Critical raw materials
17. Chemical recycling
18. CO_2 utilisation

3.1 Bio-based plastics and its recycling

Plastic is a widely used material in many industrial and daily life applications. They are the "ubiquitous workhorse material of the modern economy: combining unrivalled functional properties with low cost" (WEF & EMF 2017). Most of the plastics produced globally are derived from fossil resources. But under increasing pressure on fossil resources due to climate change and environmental consciousness, the use of biomass for plastics production has gained attraction. These so-called bio-based plastics are mainly sourced from agricultural biomass like corn, sugar cane and wheat (WEF et al. 2016). Additionally, and based on the above-mentioned interest in non-food biomass, there is also increasing interest in using so-called 2nd generation biomass e.g. crop residues such as maize stalks, waste vegetable oils, biowaste, pulp and cellulose. Furthermore, biomass derived from algae is being investigated, as it does not compete with agricultural land (De Schoenmakere et al. 2018). However, most of the activities on 2nd generation biomass based plastics are still on research level and not commercial yet.

An often-cited issue is the implication and understanding that all bio-based plastics are biodegradable and that their main value lies in this attribute. Biodegradability itself is a source of confusion when discussing recycling, because often the general public is unaware of differences between industrial composting (which occurs under controlled circumstances and constant heat) and home composting or even in-situ composting in the general environment. Within the broad term of biodegradability, industrially compostable materials are a category of materials that, under controlled composting conditions at approximately 50-60°C, biodegrade by at least 90% by weight within six months, fragments into pieces smaller than two millimetre diameter within 12 weeks and the compost obtained at the end of the process has no negative effects on plant growth (De Schoenmakere et al. 2018).

That said, for the general recyclability of bio-based plastics, especially in comparison to fossil-based plastics, the discussion of biodegradability is only of lower priority. It is important to point out that bio-based plastics strictly refer to the fact that the **feedstock is bio-based** – while they can also be biodegradable, this is an additional property that is not reflected in the term bio-based plastics.

When avoiding the pitfall biodegradability, focus can be put on the general perception that bio-based plastics are problematic and damaging for existing recycling waste streams – while some issues exist, they are often not the key barrier to implementation. The technology to recycle bio-based plastics is available and market-ready. Still, a distinction should be made between drop-in bio-based plastics and dedicated bio-based plastics:

Drop-in bio-based plastics, which are chemically identical to conventional fossil-based plastics, like bio-PP, bio-PE and bio-PET, can be and already are recycled using the same infrastructure and along with their conventional fossil-based counterparts without any issues.

They are compatible with the existing recycling systems for these plastic streams and require no further processes or investments.

Dedicated bio-based plastics, like PLA or PHA, are polymers that are not chemically identical to an existing fossil-based counterpart. Stakeholders from waste management and waste processing often claim that a separate collection of a dedicated bio-based plastic is not feasible or even potentially harmful to the existing equipment of the waste treatment plant. In fact, it would be technically possible to sort out bio-based plastics with NIR technology, if the existing systems were properly equipped. Consequently, the primary reasons why dedicated bio-based plastics are not collected separately are the high initial investment costs and the (as of yet) small sises of these streams. It is estimated that a separate bio-based plastic waste stream would become lucrative once the collected plastic waste contains at least 5-10% of the material to be separated.

In order to better align bio-based plastics with the circular economy, a study by CE Delft recommends to (Odegard et al. 2017):

- Optimise the input into the economy (sustainable agricultural practices, maximised emission reductions, minimised land-use change risks, reduced fossil resource use)
- Optimise mechanical recycling treatment (minimise losses, enable treatment of dedicated bio-based plastics in recycling)
- Treat litter as a separate problem where biodegradables are not the solution
- Use biodegradables in applications where it is functional (i.e. because applications prohibit a proper collection or because wastes are too contaminated to be properly cleaned and recycled) or offers co-benefits

The report concludes that a circular economy must and will reach a high recycling rate for (bio-based) plastics. Because of the nature of plastics (degradation after multiple recycling rounds) and existing barriers (e.g. recycled plastics not allowed for food packaging), sources of virgin plastic will still be required in the future. This input can be made more sustainable by using bio-based plastic from sustainable biomass sources. Promoting sustainable, recyclable bio-based plastics would be a strong link between the bio-based economy and the circular economy (Odegard et al. 2017).

3.2 Oleochemistry

Oleochemistry involves vegetable and animal oils and fats as well as chemicals derived from these fats and oils. They are used as raw materials or intermediates in a variety of applications and fields. The oleochemical industry is one of the oldest areas of a bio-based economy, as it has been always bio-based, utilising vegetable and animal oils and fats. Today, oleochemical production facilities are modern biorefineries that are not only based on vegetable and animal oils and fats, but also use further organic side-streams, where by-products not only from food and meat processing, but also from papermaking industries are valorised. Additionally, oleochemicals can serve as additives that enhance the recyclability of products. The most established process here is the de-inking of paper applications, where the colour of e.g. newspaper is removed. Using a side streams from the food and feed industry and by enabling recycling for bio-based products, the oleochemistry already plays an important part of the circular economy (APAG 2017).

At the same time, the oleochemistry predominantly relies on tropical oils and fats from palm kernel or coconut when using vegetable oils as sources for medium-chain fatty acids. With the sustainability of tropical oils in question, new innovations could provide solutions. The

COSMOS project (www.cosmos-h2020.eu) investigates two potential vegetable oilseed crops, camelina and crambe, and tries to create optimised sustainable value chains. In order to achieve zero waste, insects are used to digest the press cake of the oilseed crops into animal feed, fertiliser and even high-value chemical like surfactants – combining the bio-based economy with circular economy thinking (Schreven S. et al. 2018).

3.3 Utilisation of waste/side streams

Biomass is being used in a wide variety of areas today – as food/feed, for the generation of electricity and heat, for fuels, as a material and resource in the industrial sector and in the wood, paper and chemical industry. This means that there is basic competition among different uses, which is also associated with competition for land under cultivation (VCI 2007).

A shift towards increased utilisation of waste and side streams could extend the resource base without increasing the need for additional land for biomass production. Furthermore, such a development can reduce the use of energy and materials during production and use and facilitate locally clustered activities to prevent by-products from becoming wastes, increasing industrial symbiosis. Business models aiming to use waste or side streams as a resource therefore promote cross-sector and cross-cycle links by creating markets for secondary raw materials (Reichel et al. 2016).

For the chemical industry, waste and side streams from chemical plants can be of particular interest because they can potentially provide bio-based raw materials that avoid societal discussions about food crop utilisation. It is estimated that 121 million tonnes of agricultural crop and forestry residues could be generated annually in Europe, together with 46 million tonnes of forestry residues and 31 million tonnes of grass (Iqbal et al. 2016). All in all, there is a variety of waste material and side streams available for the bio-based chemistry, but while in theory these can provide large amounts of solid, liquid and gaseous material, in practice the available amount is often much smaller:

- Agricultural wastes and side streams: Within agriculture, more than half the globally harvested dry mass consists of agricultural residues and inedible biomass, such as cereal and legume straw; shoots of tuber, oil and sugar; vegetable crop stalks, leaves and shoots; and fruit and nut tree prunings. A major barrier to increasing the use of agricultural and forestry residues are the costs associated with adapting harvest logistics, which are often higher than costs of primary fossil materials. Also, for many agricultural and forestry residues, there is a lack of incentives for farmers or forest owners to collect such wastes. Local biorefining systems that smartly match residue supply and material demand need to be developed, as the wide dispersal of residues does not fit the economies of scale of the existing industrial oil-based production system (De Schoenmakere et al. 2018). However, any such strategic developments and also calculations need to keep in mind that the leftover residues provide an important and valuable input to the agricultural soil, giving nutrients back to the ground. A complete utilisation of agricultural residues would be an ecological disaster as well as create great problems for agriculture in the near term, since yields would reduce significantly without these residues left behind. A balanced approach is therefore necessary for implementing such a strategy.
- Lignocellulosic wastes: In theory lignocellulosics are the most abundant bio-based raw materials, but biorefining of cellulosic side streams is struggling with techno-economic issues. Separating the sugars required for fermentation from their

lignocellulose bonds is cumbersome, and this conversion step has been identified as a bottleneck (Wernick et al. 2016). Several research projects are working on these issues, see for example the BIOFOREVER (https://bioforever.org/) project.

- Municipal solid waste: Municipal solid waste contains food waste, which is a potential waste material for the bio-based chemistry – signifying a high amount of fermentable materials which are mixed up with non-fermentable materials, which are thus difficult to access.
- Industrial waste gases exist in profusion and are often in a relatively pure form, but microbial processes for their fermentation are immature, and there may be little incentive for companies to capture waste gases.
- Marine streams: The oceans offer large opportunities for the cascading use in the bioeconomy. These include for example the use of fisheries discards (~40% of caught fish), algal biorefineries, seaweed farming, multi-use of marine space in off-shore platforms, zero-waste and circular aquaculture, new products from jellyfish, new pharmaceuticals from marine ecosystems. Many of these technologies are still novelties, at low technology levels and/or under further developments, so that their potential to exploit bio-based resources can be further improved.

In recent years, many research projects have been conducted on topics that explore linking material flows of the bio-based economy with the circular economy. nova-Institute (Carus and Dammer 2018) mentions examples for side streams of dairy and alcohol industries used to produce organic acids and bio-based plastics, side-streams of olive and orange juice industries used for the extraction of high value organic components and proteins and fatty acids derived from the fish processing industry.

The above indicates that there are large amounts of waste and side streams available as feedstocks for the chemical industry, but often barriers exist to fully embrace the opportunities. A more concise political will to incentivise the utilisation of waste and side streams is needed. The OECD (Philp and Winickoff 2018) references the case of rice straw, stating that more than half a billion tonnes are available in Asia, but much of it is routinely burned. In Europe, regulatory barriers exist when chemical companies try to utilise waste or side streams, e.g. hygiene regulations and non-harmonised waste definitions. In some countries, the identification of a material as “waste” rather than “secondary raw material” disqualifies it from being used as a biorefinery feedstock. Furthermore, the infrastructure to collect, store and transport biomass and waste is currently not well-developed and would have to be expanded.

As a final consideration, when investigating the utilisation of waste and side streams, it should also be considered whether there is a previous, existing application for the specific stream, for example whether the stream might be relevant for soil management or animal feed.

3.4 Biodegradability of chemicals

The biodegradation of chemical substances by living organisms is one of the most important processes determining the fate of organic chemicals that enter the environment. Microorganisms play a major role in biodegradation because of their catabolic versatility and ability to adapt to a variety of environmental conditions – nature often finds its way to decompose and dismantle materials. Biodegradation can take place under both aerobic and anaerobic conditions. In the natural environment, the former occurs in upper soils or shallow waters where oxygen is present, while anaerobic degradation occurs in sediments or groundwater where oxygen is generally absent. Biodegradation is also important in wastewater treatment plants, where both aerobic and anaerobic processes are consecutively involved. When speaking about circularity, the biodegradability of chemicals that will end up in the environment is a crucial factor to consider.

One group of particular interest are lubricants. These are formulations that consist mostly of a base oil with the intention to reduce friction between two surfaces in contact. The properties of the base oil are usually modified by adding small amounts of different additives. Lubricants are predominantly synthesised from fossil resources and are then used in a multitude of applications in the domestic, industrial and transport industries. Within this wide range of applications, bio-based lubricants make up only a small share of the total market, in particular in areas where they offer superior biodegradability characteristics compared to fossil derived lubricants.

The bio-based lubricants market is driven by regulations on total-loss applications or improved performance for certain applications. In total-loss applications the lubricant ends up in the environment, for example from the use on chainsaws. There are several EU Member States, where bio-based lubricants are compulsory for use in total-loss applications in environmentally sensitive areas (Krop 2014). This can be explained by the fact that bio-based lubricants offer a safer and less toxic work environment due to higher flashpoints, constant viscosity and less oil mist and vapor emissions (State of Washington 2011), which explains why the major user group of bio-based lubricants is the automotive industry, using more than 56% of the overall share. The market for bio-based lubricants mainly exists in Europe and the US. Outside of these regions it is limited, largely due to their high costs, which can be twice as high compared to fossil lubricants (Tsagaraki et al. 2017).

However, the need for biodegradable lubricants that are non-toxic has caused the market share of bio-based lubricants to increase (Tsagaraki et al. 2017). Environmental concerns and strict standards for management of leakage, maintenance and disposal of unused fossil-derived lubricants provide evidence for the growth and development of this sector. In a future that is likely to put larger focus on climate-friendly, low-toxic and environmental-friendly materials, biodegradable chemicals can play an important role in a circular economy for applications, where the release of the chemical into the environment cannot be prevented (surfactants in detergents and cleaning agents are another excellent example of such an application group).

Composting is a well-developed process that has been applied for a long time to treat organic waste. The efficient composting of bio-based waste prevents greenhouse gas emissions resulting from decay by facilitating controlled, aerobic degradation, avoiding CH_4 emissions. Additionally, composting provides a natural soil additive that acts as a carbon sink and nutrient source. Using compost on soil not only improves its structure and replaces the need for some artificial chemical-based fertilisers. Although the production of such fertilisers is often energy intensive, replacing them with compost does not always deliver a net benefit for greenhouse gas emissions. Instead, recent studies have shown that compost applied in the production of growth media can achieve high greenhouse gas emission reductions (Pfau S. et al. 2019). In recent years, industrial-scale composting has emerged, but the technology is still new, lacks optimization and requires further developments, additional technologies and improved efficiency (Onwosi et al. 2017). Also, organic recycling as an expansion of circular economy still has to find its position and acceptance in the circular economy, e.g. through new legislation on fertilisers, including bio-based ones (Carus and Dammer 2018).

3.5 Ecodesign

The ecodesign concept was introduced even before the notion of a circular economy took hold. It describes a systematic and comprehensive approach to the consideration and design of products with the aim of reducing the environmental impact over the entire life cycle through improved product design. In the planning and design phase of a product, manufacturers can influence each phase of the value chain and the material life cycle and promote ecological innovations. The environmentally compatible design of products requires quantitative and qualitative assessment standards and supporting instruments. As a result, products can be (Reichel et al. 2016):

- designed for a longer life, enabling upgrading, reuse, refurbishment and remanufacture
- design based on the sustainable and minimal use of resources and enabling high-quality recycling of materials at the end of a product's life
- improved to substitute hazardous substances in products and processes, enabling cleaner material cycles.

A key principle for ecodesign is the waste hierarchy, as described in the European Waste Framework Directive (EC 2009). This hierarchy defines a priority order for waste management, starting at the prevention of waste as the preferred choice, through reuse, recycling, other (e.g. energy) recovery, to disposal as the least preferred option. In that sense, ecodesign strives to prevent first of all, and then considers reuse prior to recovery. Because both the circular economy and the bio-based economy aim to develop a more sustainable economy in general, the ecodesign principles align well with both concepts. Back in 2012, Bas Eickhout from the European Parliament Greens called for the ecodesign directive “to cover also non-energy related dimensions, such as recycling content, bio-based content, and the use of primary resources” (Eickhout 2012). And in its resolution of 31 May 2018 on the 'implementation of the Ecodesign Directive', the European Parliament noted that the Ecodesign Directive provides significant potential for improving resource efficiency that is still untapped and stressed the need to set up of minimum resource efficiency criteria covering criteria like durability, robustness, reparability and upgradability, but also sharing potential, reuse, scalability, recyclability, possibility of remanufacturing, content of recycled or secondary raw materials, and the use of critical raw materials.

It has been noted that the definitions of the waste hierarchy are all based on the assumption that a product will at a certain point turn into waste. To a certain degree, the reliance on waste is not compatible with the context of the circular economy, where waste does not exist (or should at least be minimised as much as possible) (den Hollander et al. 2017). Instead, for the context of the circular economy, the ecodesign principles would have to be adapted. The authors argue that without waste as an option, extending useful lifetime is the most effective way to preserve resources.

3.6 Biorefineries

In a biorefinery, biomass is transformed into a spectrum of valuable products such as chemicals, materials, feed and fuels, electricity and, as a by-product, heat. Biorefinery concepts aim to utilise biomass to the fullest extent, but also apply specific technologies to isolate components, prevent waste, logistics aspects as well as value chain aspects. The European Commission has encouraged that biorefineries should adopt a cascading approach that favours highest value added and resource efficient products over e.g. bioenergy (EC 2012).

Biorefining in a wider sense is established for producing products such as beer, sugar, vegetable oils, cellulosic fibres and wine, but more advanced biorefineries are developed with the intention to process more diverse raw materials, including agricultural, forestry and marine biomass resources These biorefineries can process the wide range of biomass into a spectrum of marketable products and energy, like feed, fibres, bulk and fine chemicals, fertilisers, biofuels, power and heat. By combining different products in a highly integrated production process, available sources of biomass can thus be used more effectively (De Schoenmakere et al. 2018).

Currently, there a number of projects with a focus on biorefineries. The BIOSKOH project (https://bioskoh.eu/), for example has the general ambition to demonstrate the potential for a series of new second generation biorefineries for Europe, investigating a 55 kton second generation biorefinery to produce cellulosic ethanol.

The EMBRACED project (https://www.embraced.eu/project) aims to demonstrate, in a relevant industrial environment, a replicable, economically viable and environmentally sustainable model of integrated biorefinery based on the valorisation of the cellulosic fraction of post-consumer absorbent hygiene products (AHP) waste in producing bio-based building blocks, polymers, and fertilisers. The biorefinery will use a circular economy approach, closing the cycle of raw materials and minimising the use of primary resources.

Both examples indicate how biorefineries, and the bio-based chemical industry, overlap with the targets of the circular economy. Biorefineries can deliver a variety of bio-based products to the chemical industry and at the same time provide the opportunity for joining bio- and circular economy principles, especially when using second-generation feedstocks from outside the food and feed sector.

3.7 Critical Raw Materials

Raw materials are linked to all industries across all supply stages, but some of them are of higher concern in terms of sustainable supply. Such raw materials are referred to as critical raw materials (CRMs). CRMs are of high economic importance for the EU and have a high risk of supply disruption. In 2017, the EU published an updated list of CRMs; examples include rare earth elements, cobalt, tungsten and phosphates (European Commission 2017). The production of several chemicals and fertilisers in Europe relies on multiple CRMs, the main applications include their use in the production of catalysts, phosphorous fertilisers, micronutrient fertilisers (e.g. boron), polymers, pharmaceutics and dyes.

According to the findings of a Raw Material System Analysis study (BIO by Deloitte 2015), CRMs used in several chemical applications are lost to the environment due to dissipative use or landfilling. Examples include natural graphite in lubricants, silicon, tungsten in catalyst production as well as borates and phosphates in fertiliser production. Increasing the circularity in the chemical industry could reduce these losses and keep the CRMs in the value chains longer. One link to the bio-based economy is the case of borates and phosphates, where the sources of secondary materials are biogenic wastes, like manure or bio- and food wastes from functional recycling and even from wastewater. In the case of borate, the EU recycling in 2012 amounted only to 465 tons, while close to 90,000 tons were imported. And in case of phosphate rocks, largely used for fertiliser production, 180,000 tons of phosphate were recycled, while roughly 1.8 million tons were imported (BIO by Deloitte 2015).

The chemical industry can play an important role towards increasing the circularity of CRMs: through innovation and the development of new technologies, value chains can be developed that recover nutrients and phosphates from waste streams. One current example is the NEWFERT project (http://newfert.org/), which intends to turn bio-based solid and liquid residues (ashes and struvite) into bio-based fertilisers. The project is also in line with the best practice case recommendations of the JRC report on critical raw materials and circular economy (Mathieux F. et al. 2017)

3.8 Chemical Recycling

Next to the established mechanical recycling for a circular use of plastic waste, chemical recycling is emerging slowly as an alternative–but currently cost intensive–way of re-using materials. The process results in re-obtaining molecular fractions of the plastics to be used as building blocks, by combustion, pyrolysis or gasification. This way chemical recycling allows to start an entirely new production and fresh value chains from used plastic materials. These are not restricted to the reuse as plastics (thus also avoiding a loss of quality), since chemical recycling can lead to the synthesis of diverse chemicals, methanol, ethanol and hydrocarbons, as well as purified, food grade CO_2. Therefore, chemical recycling could also be applied to materials and products from the bio-based economy and bio-based chemical industry.

3.9 Direct CO_2 utilisation

With climate change rising higher on the political agenda, the utilisation of the greenhouse gas carbon dioxide is moving more and more into focus. Despite CO_2 being a rather inert gas, a multitude of already established uses can be identified that rely on renewable energy to put the carbon into use again. They can be structured into three main categories: Direct use (e.g. in greenhouse, beverages or dry ice), mineral use (e.g. cement curing, carbonate production or water neutralisation) and organic chemistry use. The main CO_2 application as of today is urea synthesis from ammonia, but there are concentrated and well-developed efforts towards power-to-gas (methanisation), power-to-liquid (synthetic naphtha and kerosene) and methanol production chains based on carbon dioxide. Furthermore, research projects, industry and start-ups also investigate chemical pathways to turn CO_2 from different sources into products as diverse as fine chemicals like formic acid or carbamates, polyols, polycarbonates, polyurethanes, biotechnological pathways towards ethanol, butanol and lactic acid and even proteins.

Utilising CO_2 can act as a crucial step in the circular economy concept, because it would be a potent tool for climate change mitigation, potentially allowing to capture CO_2 instead of releasing it to the atmosphere. Based on the concept of renewable and recycled carbon, the bio-based economy connects via the carbon that is stored in its biomass based raw materials.

4. Conclusion

The concept of the bio-based economy and the circular economy have similar targets and are overlapping to a larger extent, but neither is fully part of the other. In other words: the circular economy is not complete without the bio-based economy and vice versa. The intersection between the two concepts is called the “circular bioeconomy” and there are clear intersections to be identified and advantages to be gained by aligning the two concepts.

The most central theme of the circular bioeconomy is the utilization of bio-based waste materials, which could at the same time reduce the dependency on fossil resources and drastically reduce waste in general (Hetemäki et al. 2017). The huge volumes of organic side and waste streams from agriculture, forestry, fishery, food & feed and organic process waste can only be integrated in the circular economy through bio-based economy processes, while the bio-based economy will hugely profit from increased circularity (Carus and Dammer 2018). A sustainable and circular bioeconomy would retain its resources at highest value for as long as possible through cascading biomass use and recycling, and at the same time ensure that the available natural capital is preserved. (De Schoenmakere et al. 2018).

(Langeveld et al. 2016) describe the following picture of a circular bioeconomy for the Netherlands:

> *Supply and value chains, instead of originating at the sources of fossil feedstocks with subsequent transportation across oceans, have the opportunity to be developed more locally. This would create jobs much closer to the feedstocks: in particular here is a chance for addressing the policy goal of rural regeneration. But this would create the need for a new generation of both R&D and production companies that is almost entirely missing at present. New skills, training and education will be required on a large scale, and the higher education sector would need to be adjusted to provide this. In the Netherlands alone, a demand for 10,000 bio-based experts is expected in the next eight years.*

However, some potential issues for the circular bioeconomy exist. These include:

- The well-described tension or non-level playing field between biomass as a feedstock for bio-based chemicals and materials and its use in bioenergy applications. This in a broader sense describes a policy conflict between industrial and environmental policy
- Waste markets can be disrupted as some waste materials that currently go to recycling, landfill or incineration could in the future be bound for biorefineries.
- Cascading usually increases the efficient use of resources, but a direct connection to reduced GHG emissions is not guaranteed. Also, along the cascade products can accumulate toxic or critical substances, which can serve as barriers for their further processing or recycling.

The chemical industry could play (and already plays) an integral part in developing the circular bioeconomy. Harris et al. (Harris et al. 2018) conclude that the circular economy “tends to focus only on the biodegradability aspect of renewables, whilst largely neglecting their ability to be reused and recycled”. Looking at the mentioned examples in this document, the chemical industry can help to align the bio-based and the circular economy by demonstrating the feasibility of reusing or recycling products made from renewable materials and by creating value-added products from reused or recycled bio-based raw materials.

To get there, both the private and public sector have to deploy concentrated efforts. Currently, the bio-based and circular economies are largely considered as two separate entities, and policy is focused largely on its own targets. Here, the public sector could create more synergy by tighter connecting regulations, policies and innovation targets. The OECD (Philp and Winickoff 2018) concludes that "*the synergies between the bioeconomy and the circular economy concepts are there to be exploited. This will need a combination of initiatives by the public and private sectors. However, there are many policy challenges and goals for the public sector to act upon first, as much of what has been described is too highly risk-laden for the private sector to contemplate alone*."

The European Environment Agency (De Schoenmakere et al. 2018) recommends that:

- Policy interventions should be geared towards the reduction of environmental pressures along the entire value chain.
- Bio-based approaches should be tailored to the specific use context in order to maximise the benefits of bio-based and biodegradable products.
- Technological innovation should be embedded in wider system innovation that also tackles consumer behaviour, product use and waste management.

When considering the overall incentive of the RoadToBio project, which is to increase the bio-based share of raw materials used in the chemical industry, the alignment of bio-based and circular economy can provide further incentives to utilise larger amounts of biomass, derived from agriculture, forestry, marine resources, but also from waste fractions. In the future, our fossil-based economy will have to evolve towards a renewable resource base, and an aligned approach of both the bio-based and the circular economy can play an important part in that development.

The organic chemistry, unlike the energy sector, cannot decarbonise. The chemical industry needs to switch to using renewable and recycled carbon in chemicals production whilst also decarbonising chemical production processes. Renewable and recycled carbon can stem from biomass, from recycling or from direct CO_2 usage, and all three sources would be covered in a well-developed circular bioeconomy concept, which still considers the individual aspects of the bio-based and the circular economy independently.

5. References

APAG (2017). The European Oleochemical Industry at a Glance – Traditional and innovative products from sustainable sources.

BIO by Deloitte (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials, Prepared for the European Commission, DG GROW. https://ec.europa.eu/jrc/en/scientific-tool/msa

Carus, M. (2017). Bio-based economy and climate change - Important links, pitfalls and opportunities. www.bio-based.eu/nova-papers

Carus, M. and Dammer, L. (2018). The „Circular Bioeconomy" – Concepts, Opportunities and Limitations. www.bio-based.eu/nova-papers

Carus, M. and Raschka, A. (2018). Renewable Carbon is Key to a Sustainable and Future-Oriented Chemical Industry. www.bio-based.eu/nova-papers

De Schoenmakere, M., Hoogeveen, Y., Gillabel, J. and Manshoven, S. (2018). The circular economy and the bioeconomy - Partners in sustainability.

den Hollander, M. C., Bakker, C. A. and Hultink, E. J. (2017). Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology, 21 (3), 517-25.

EC (2009). Waste Framework Directive (2008/98/EC) or Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Download at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1548776164367&uri=CELEX:32008L0098

EC (2012). European Commission. Innovating for Sustainable Growth – A bioeconomy for Europe. Publications Office of the European Union, Luxembourg Download at

EC (2015). Communication from the Commission to the European Parliament, the Council, the European Economi cand Social Committee and the Committee of the Regions. Closing the loop - an EU action plan for the Circular Economy. Brussels 02 December 2015. Download at

Eickhout, B. (2012). A strategy for a bio-based economy.

European Commission (2017). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on the 2017 list of Critical Raw Materials for the EU, COM/2017/0490 final. Download at

GBS (2015). Communiqué Global Bioeconomy Summit 2015, Making Bioeconomy Work for Sustainable Development. https://gbs2015.com/fileadmin/gbs2015/Downloads/Communique_final.pdf

Harris, S., Staffas, L., Rydberg, T. and Elin, E. (2018). Report C296 – Renewable materials in the Circular Economy.

Hetemäki, L., M. Hanewinkel, B. Muys, M. Ollikainen, M. Palahí and A. Trasobares (2017). Leading the Way to a European Circular Bioeconomy Strategy, From Science to Policy 5.

Iqbal, Y., Lewandowski, I., Weinreich, A., Wippel, B., Pforte, B., Hadai, O., Tryboi, O., Spöttle, M. and Peters, D. (2016). Maximising the yield of biomass from residues of agricultural crops and biomass from forestry, Final Report.

Krop, H. (2014). Greening your portfolio: use the EU Ecolable for Lubricants (why, how, what and future). 2014. Download at http://www.innovhubssi.it/c/document_library/get_file?uuid=0305bf4a-e917-4b0e-ab5abd61ad16580e&groupId=11654.

Langeveld, J. W. A., K.P.H. Meesters and Breure, M. S. (2016). The Bio-based Economy and the Bioeconomy in the Netherlands.

Mathieux F., Ardente, F. and Silvia Bobba, P. N., Gian Andrea Blengini, Patricia Alves Dias, Darina Blagoeva, Cristina Torres de Matos, Dominic Wittmer, Claudiu Pavel, Tamas Hamor, Hans Saveyn, Bernd Gawlik, Glenn Orveillon, Dries Huygens, Elena Garbarino, Evangelos Tzimas, Faycal Bouraoui, Slavko Solar (2017). JRC Science for Policy Report – Critical raw materials and the circular economy.

Odegard, I., Nusselder, S., Lindgreen, E., Bergsma, G. and de Graaff, L. (2017). Biobased Plastics in a Circular Economy – Policy suggestions for biobased and biobased biodegradable plastics.

Onwosi, C. O., Igbokwe, V. C., Odimba, J. N., Eke, I. E., Nwankwoala, M. O., Iroh, I. N. and Ezeogu, L. I. (2017). Composting technology in waste stabilization: On the methods,

challenges and future prospects. Journal of Environmental Management, 190 17.

Pfau S., Hanssen S., Straatsma M., Remon Koopman K., Leuven R. and Huijbregts, M. (2019). Life cycle greenhouse gas benefits or burdens of residual biomass from landscape management. Journal of Cleaner Production,

Philp, J. and Winickoff, D. E. (2018). Realising The Circular Bioeconomy. OECD Science, Technology and Industry Policy Papers, No. 60

Reichel, A., De Schoenmakere, M. and Gillabel, J. (2016). Circular economy in Europe: Developing the knowledge base. http://www.eea.europa.eu/publications/circular-economy-in-europe

Schreven S., Dicke M. and J., v. L. (2018). Going in circles? Assessing edible insects for bioconversion of crop residues, Poster presented at the SDG-Conference “Towards Zero Hunger: Partnerships for Impact“. Wageningen, The Netherlands 30-31 August 2018. Download at http://cosmos-h2020.eu/media/2018/12/SDG-poster-v4.pdf

State of Washington (2011). Environmentally Preferable Purchasing Fact Sheet – Biolubricants. Download at

Tsagaraki, E., Karachliou, E., Delioglanis, I. and Kouzi, E. (2017). BIOWAYS Bio-based economy: network, innovate, communicat – D2.1 Bio-based products and applications potential.

VCI (2007). Biomass as a Resource for the Chemical Industry – Key findings of an IFEU study and conclusions of the VCI.

WEF, Foundation, E. M. and Company, M. (2016). The new plastics economy – Rethinking the future of plastics.

WEF & EMF (2017). World Economic Forum and Ellen MacArthur Foundation. The New Plastics Economy – Catalysing Action.

Wernick, D. G., Pontrelli, S. P., Pollock, A. W. and Liao, J. C. (2016). Sustainable biorefining in wastewater engineered extreme alkaliphile Bacillus marmarensis. Nature Scientific Reports, 6 (20224 (2016)),