BIOPEN: the open innovation platform to stimulate the business and innovation potential of the bio-based sector in Europe

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Deliverable 3.2 - Reports on the five prospective studies

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List of Acronyms

ABS	Acrylonitrile Butadiene Styrene
AO	Antioxidants
BBD	Stichting Biobased Delta
BCM	Bioeconomy Cluster Management Gmbh
BPA	Bisphenol-A
BTX	benzene, toluene, xylene
CAGR	Compound annual growth rate
CLIB	Cluster Industrielle Biotechnologie 2021 E.V.
CT	computed tomography
CTECH	Ciaotech Srl
EUN	Europe Unlimited S.A.
FDCA	Furandicarboxylic acid
GHG	Greenhouse gas
HDPE	high-density polyethylene
HIPS	High Impact Polystyrene
KETs	Key enabling technologies
LA	Lactide
LC	Lignocellulosic
LCP	Liquid Crystal Polymer
LDPE	low-density polyethylene
NTUA	National Technical University of Athens
PAI	Polyamide-Imide
PBRs	Photobioreactors
PBT	Polybutylene Terephthalate
PC	Polycarbonate
PCL	Polycaprolactone
PE	Polyethylene
PEEK	Polyetheretherketone
PEF	Polyethylene Furanoate
PEG	Polyethylene glycol
PEI	Polyetherimide
PES	Polyether Sulfone
PET	polyethylene terephthalate
PF resins	phenol–formaldehyde resins
PHAs	poly(hydroxyalkanoates)
PLA	Polylactic acid
PLLA	Polylactic acid

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PMMA	Polymethylmethacrylate
POM	Polyoxymethylene
PP	polypropylene
PPO	Polyphenylene Oxide
PPS	Polyphenylene Sulfide
PPT	Polypropylene Terephthalate
PS	polystyrene
PSU	Polysulfone
PUFA	Polyunsaturated fatty acids
PUR	polyurethanes
PVB	polyvinyl butyral
PVC	polyvinyl chloride
SNG	Synthetic Natural Gas
TRL	Technology readiness level
TURKU	Turku Science Park Oy Ab
WPCC	Stowarzyszenie Zachodniopomorski Klaster Chemiczny Zielona Chemia

1 Executive summary

Today's fossil-based economy has produced major problems related to climate change attributed to excessive CO_2 emissions caused by the almost complete reliance on crude oil and gas for the production of energy and carbon-based products. This entails risks for socio-economic instability due to rapid and excessive climate change as well as fluctuations in prices and supply on the short, medium and longer term.

The goal of this document is to conceptualise the generic bio-based product/process value chains and define the key enablers involved. The document will be organized, hosted and made available to the users of the BIOPEN Open-Innovation platform by the dedicated knowledge centre.

It reports on the findings of the 5 perspective studies conducted in the course of Task 3.2 of WP3. Value chains in the areas of polymers, packaging, bioaromatics, wood and algae products are examined in regards to their environmental social and economic sustainability, and the level of technological maturity.

The report identifies weak points in the route for realizing these value chains, but also points to the strengths of EU and suggests measures and strategies to expedite the development of bio-based products at commercial scale.

The next sections describe the goals of the studies, the method followed to reach the desired results and it further justifies the connection of the studies as a natural outcome of the relation of the feedstocks intermediates and final products which share many common features.

Each study follows the value chain from feedstock, it comments on the technologies and emphasizes on the market features. Products are examined having in mind the possibility of early entry to the market attached to the TRL of the process and the economic sustainability of the whole process from feedstock to end users.

The reports on the studies contain individually highlights and key conclusions on the examined value chains and general conclusions are drafted at the end, having a general perspective and followed by suggested policies and measures for the fast and safe transition to the bio-based economy.

2 INTRODUCTION TO STUDIES CONTENT AND METHODOLOGY

2.1 THE STUDIES IN THE CONTEXT OF THE BIOPEN PROJECT

Task 3.2 deployed five detailed perspective studies on major sectors of the bio-economy. NTUA brought expertise gained through research projects (BIOCORE, RENESENG, D-FACTORY, RESYNTEX) directly related to the development of paths towards bio-products driven by market-oriented end user applications; biofuels, niche chemicals, polymers, textiles, food and feed. The perspective studies are classified into two levels: raw materials and end products. Raw materials include lignocellulosic biomass, micro and macro algae, and waste. Products are categorised into bio-energy, bulk products (eg. ammonia), biofuels and energy carriers, intermediate chemicals (syngas, glucose, lipids etc.). Raw materials are associated with primary and secondary products and the resulting value chains are evaluated accordingly; lignocellulosic biomass is examined mostly for value chains involving commodities and bulk chemicals and products (for wood applications for example) and to a lesser extent for biofuels and specialties. Algae are targeted mainly for specialties but also energy carriers, and waste will be studied in bio-energy production value chains (this is state-of-the-art) with secondary alternatives the production of commodities (this is the trend and more interesting). The first output of the perspective studies is used in the Requirements Analysis of task 2.1. Each value chain under study will contain more than one end-product and will address multiple applications, since the multiple paths can enhance business perspective and sustainability for the companies in the value chain. In collaboration with the cluster partners of BIOPEN (WPCC, TURKU, CLIB, BCM and BBD), NTUA managed a network of academic, technological and financial and innovative venture experts (brought by CTECH and EUN) from within the project's ecosystem and outside when this is deemed necessary, to perform the perspective studies on upcoming technologies and downstream markets for the following bio-products and applications.

2.2 SCOPE OF THE STUDIES

The driver for the studies is the need to answer a number of questions related to the bio-based industry value chains. Some of the most important questions are the following:

- What are the products that bio-based products will replace and in what applications?
- What is the current volume of conventional products produced and used, and what is the future projection for the consumption of these products?
- What are the feedstocks for the conventional products and what are the production processes for the conventional products?
- What are the feedstocks for the bio-based products, and what is the availability of these feedstocks, in terms of quantity, location, and through time?
- What specifications will the bio-based products have to meet for replacing conventional products?
- What are the possible new applications of the bio-based products?
- What are the gas and challenges for the proliferation of the biobased products?
- What are the most applicable recommendations for immediate and long-term decision making?

To answer these questions different viewpoints are adopted. These include: technological efficiency and maturity, and supply chain advancement state, while the analysis considers three groups of criteria related to economic sustainability, environmental impact and social benefits.

2.3 LIST OF PERSPECTIVE STUDIES ON MAJOR SECTORS OF THE BIO-ECONOMY

1. Environmentally friendly coatings and packaging materials with specific functional properties derived from biorefinery and biotechnological processes (WPCC)

2. Functional polymer and oligomer products (including thermoplastics and natural rubber), functional carboxylic acids and amines, surfactants peptides with adhesive properties, produced through biotechnological pathways using fermentation and metabolic engineering (CLIB).

3. Products and applications based on lignocellulosic feedstock, mainly wood (BCM):

- Attractive and ecological alternatives to tropical timber
- Innovative bio-based materials made from wood
- Bio-based chemistry from wood as a raw material (polymers from cellulose, hemicellulose and lignin)
- Syngas for Synthetic Natural Gas (SNG), diesel, or other biofuels e.g. methane, methanol, and dimethyl ether via catalytic processes, and the production of bulk chemicals (e.g. ammonia)
- Other energy carriers (biogas, pellets)

4. Alternative aromatics from green raw materials for the production of synthetic materials, chemicals and coatings, like paints and glues (BBD)

5. Algae and seaweed ingredients in food products, for the purification of wastewater, and as a green raw material for niche chemical and high added value products (carotene, lipids), fine chemicals for the food and pharmaceutical industries such as AO (antioxidants), PUFA (Poly-unsaturated-fatty-acids), pigments and phycocolloids but also bioplastics and biodiesel (BBD)

2.4 Relationship of the 5 sectors and the methodological and presentation approach

2.4.1 Links between the 5 sectors under study

By examining the list of the 5 major sectors of the bio-economy presented in Section 2.3, it can be seen that there is a specific hierarchal relationship between them; Biopolymers and bioplastics are the most general bioproduct categories and are indicative of the general bio-based products potential. Coating and packaging materials fall under the biopolymers and bioplastics product category. Although aromatics can be considered as a product group with a separate market, are actually chemical precursors or are used as solvents and reactants for the production among many other chemicals for the products of the two previous categories, namely the polymer and coating products. Wood-based products and chemicals have the larger number of applications in the production of biopolymers sector. The only sector not directly linked to the 4 aforementioned sectors is the micro and macro algae sector.

Because the first 4 sectors are related as described, the results and findings for the biopolymers and bioplastics sectors - especially with respect to the market potential - are relevant for the other 3 sectors as well. Of course, for the coating and packaging materials, the discussion moves in further depths and many others aspects are examined for the categories of aromatics and wood-based products which are not necessarily linked to the biopolymer sector. Thus, the following notes on addressing these studies are listed below;

> **Note 1:** Although each study is self-contained, the results of the at least 4 first studies have to be treated under a common perspective. One additional reason for this is that the products in most cases compete against each other for the same feedstock but also technical, and financial resources.
>
> **Note 2:** Because of the shared features of the first 4 sectors, a common methodology is used for assessing all 4 of them is common and is described next.

2.4.2 Methodology used for the studies

Bioproducts are replacing conventional products, therefore the methodology firstly assesses the market status and trends for the conventional products.

Then, it is methodologically relevant to match bioproducts to the replaced conventional.

The methodology includes the assessment of the properties of bioproducts and compares them to standards and specifications for market applications

Then it assesses

- feedstock availability
- technological maturity
- cost factors (production, distribution etc.)

The reports address different stakeholders distributed along the value chain of bioproducts. These stakeholders are identified and classified accordingly.

The methodology includes the identification of gaps and challenges faced when the bioproducts are meeting with the perspective of industrial scale production and are introduced to the market.

It continues with suggesting policies and incentives

Close with recommendations for decision making

The methodology consists of the analysis of the data collected from literature sources and other sources (databases, repositories, platforms). The analysis considers mostly economic features, while environmental impact and social benefits criteria are addressed in the forthcoming deliverable 3.3. Stakeholders of the value chains are identified among the BIOPEN partners as well as external actors.

2.4.3 The content of the studies

The studies first explore the current market volumes Europe and worldwide for conventional polymers and biopolymers accordingly. Applications are discussed for the conventional and biobased groups of products. Coating and packaging bio-products are then discussed as a special case of biopolymers with emphasis on new products and new applications ex. antibacterial food packaging. Special properties of bio-coating and packaging material are discussed next with respect to standards and specifications. Aromatics as conventional products are discussed next, along with applications, technologies, volumes, markets and trends. The bio aromatics value chain is contrasted to the fossil-based value chain in terms of volumes technology and cost. Wood is examined as a feedstock for biobased products issue with respect to location, volumes, perspectives and non-chemically processed products, chemicals products. The algae sector is presented next with respect to algae bioproduct value chains and their perspectives and limitations. Along each value chain the related stakeholders are identified classified accordingly. Gaps and challenges for the market uptake of the biobased products are presented next followed by recommendations for decision making in policy, investment and technological level. The report ends with overall conclusion from the 5 perspective studies.

2.4.4 Order of studies presentation according to the product sectors relation

The studies in this deliverable are presented according to the following order:

1st is presented the biopolymers and bioplastics study (initially appearing 2nd in the description of work): because it is more general and indicative of the general bio-based products potential.

2nd is the coating and packaging materials study (initially appearing 1st in the description of work), because it is a subcategory of the biopolymers.

3rd is the study on aromatics (initially appearing 4th in the description of work) because these constitute the specific starting materials for the two categories of materials listed above.

4th is the study on wood-based products and chemicals (initially appearing 3rd in the description of work) because these are the precursors of the aromatics of the immediately previous category (aromatics).

5th comes the study on algae bio products as independent category (initially 5th and remains 5th).

3 Perspective studies

3.1 PERSPECTIVE STUDY 2 – FUNCTIONAL POLYMER AND OLIGOMER BIO-BASED PRODUCTS

3.1.1 Introduction

This study assesses the potential of the biobased polymers and plastics on the generic level of the market sizes and trends. It also lists the most prominent fields of applications for the biopolymers and maps biopolymers against their conventional counterparts with respect to specific applications. The study builds the base for assessing the potential of the more specific group of coatings and packaging biobased materials examined in the second study.

3.1.2 The market of polymers and plastics

The markets for polymers are examined first by assessing total volumes and types of polymers used worldwide, which are then compared with the current and projected global bioplastics production. According to the Polymer and Composites Industry Association (RAPRA), in 2003 the total global consumption of polymers in solid form (i.e., not adhesives, paints, binders) was 160 million tonnes (Pardos 2004), while (Ambekar et al. 2010) report a steady increase in total plastics consumption over the past 50–60 years and indicates that this figure reached 260 million tonnes for 2007. As of 2016, plastics production has already exhibited a dramatic increase, reaching 335 million tonnes (Consultic Marketing & Industrieberatung GmbH 2017). Figure 1 illustrates the global plastic production from 1950 to 2016 in million metric tons (PAGEV 2016; Statistica 2018). Although worldwide the total production/consumption of plastics has increased significantly, with a 70% increase from 2000 to 2016, in Europe the plastics production follows an almost constant rate of production (see black line in the chart of Figure 1). The growth has been witnessed mostly in Asia for the past twenty years and now in the USA again because of low cost production of shale gas and oil.

BIO-BASED INDUSTRIES Public-Private Partnership | Bio-based Industries Consortium | Horizon 2020 European Union Funding for Research & Innovation

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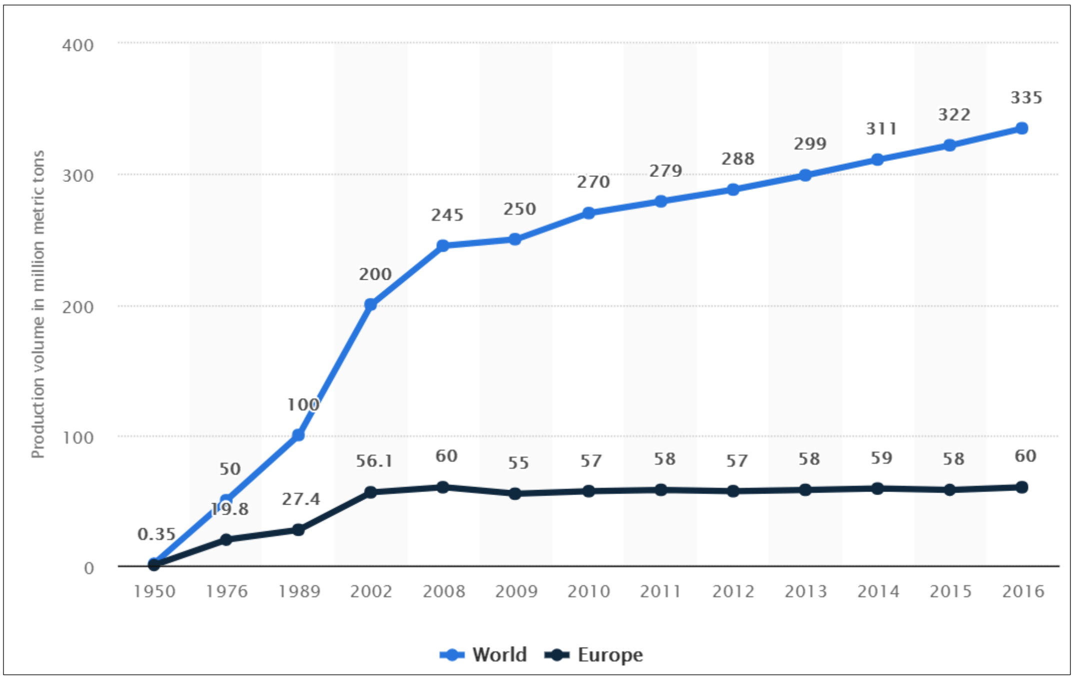


Figure 1 Global plastic production from 1950 to 2016 (in million metric tons), Source: (PAGEV 2016)

Figure 2 and Figure 3 report on the global and European production data and the distribution of global plastics material production (Plastics Europe 2017). The global market for plastic products is growing at about 3% year on year, according to research from the Business Research Co. (Philadelphia) in its report, Plastics Product Manufacturing Global Market 2017. It was worth $1.06 trillion in 2016 and will grow to $1.175 trillion by 2020. The biggest segment is plastic packaging materials and unlaminated film and sheet manufacturing, which accounts for about 20% of the total (Goldsberry 2017).

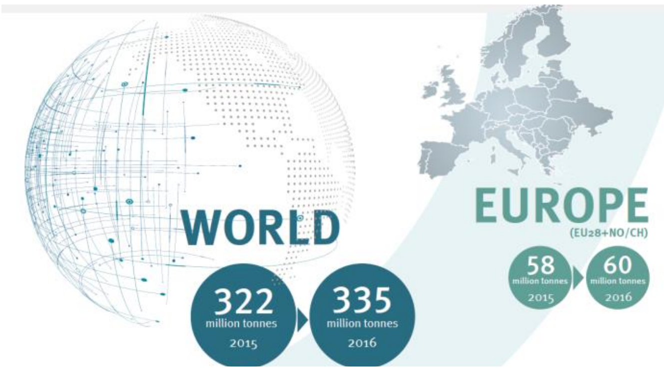


Figure 2 World and EU plastics production data[1]

[1] Source: PlasticsEurope (PEMRG) / Conversio Market & Strategy GmbH

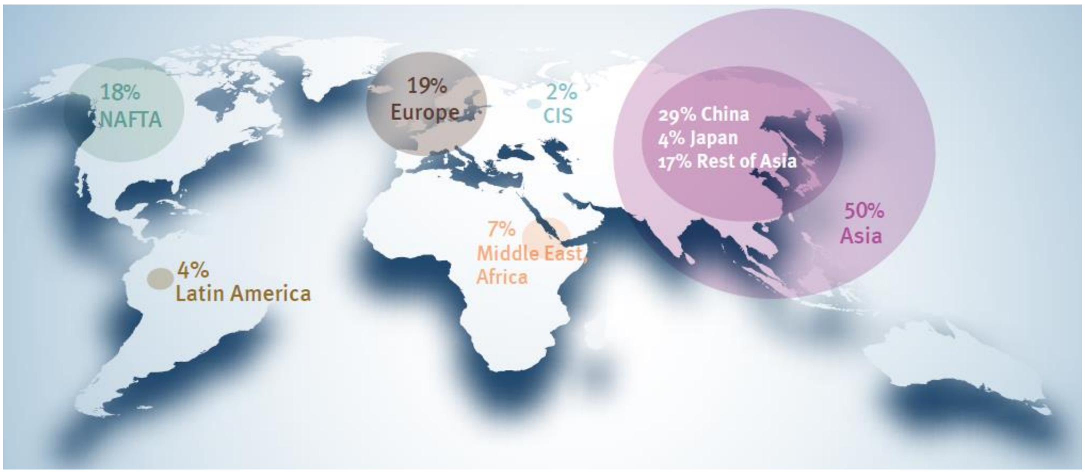


Figure 3 Distribution of global plastic materials production[2]

Figure 4 reports the EU plastics converter demand according to the different European countries, which includes plastic materials (thermoplastics and polyurethanes) and other plastics (thermosets, adhesives, coatings and sealants). It does not include PET fibers, PA fibers, PP fibers and polyacryls-fibers. Six European countries (Germany, Italy, France Spain, UK, Poland) and the Benelux cover almost 80% of the European demand in 2016 (49.9 m t).

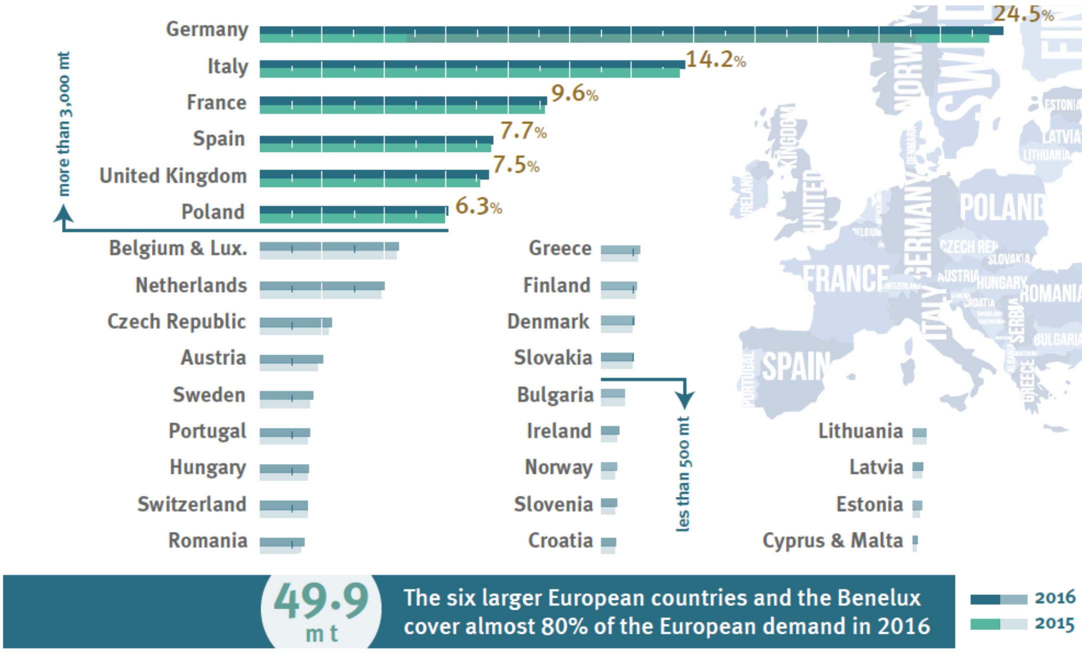


Figure 4 Plastics EU converter demand per country European[3]

[2] Source: PlasticsEurope Market Research Group (PEMRG) / Conversio Market & Strategy GmbH
3 Source: PlasticsEurope Market Research Group (PEMRG) and Conversio Market & Strategy GmbH (Consultic GmbH for 2015 data)

3.1.3 The market and perspective of the biopolymers market

In contrast, the global production of bioplastics for 2017 was 2 million tonnes divided into 0.9 of biodegradable versus 1.1 of non-biodegradable million tonnes of bioplastics (European Bioplastics 2017). The projections for the production of bioplastics for 2022 is 2.4 million tonnes (see Figure 5). With less than 1% share for bioplastics this is an encouraging perspective, showing ample space for growth.

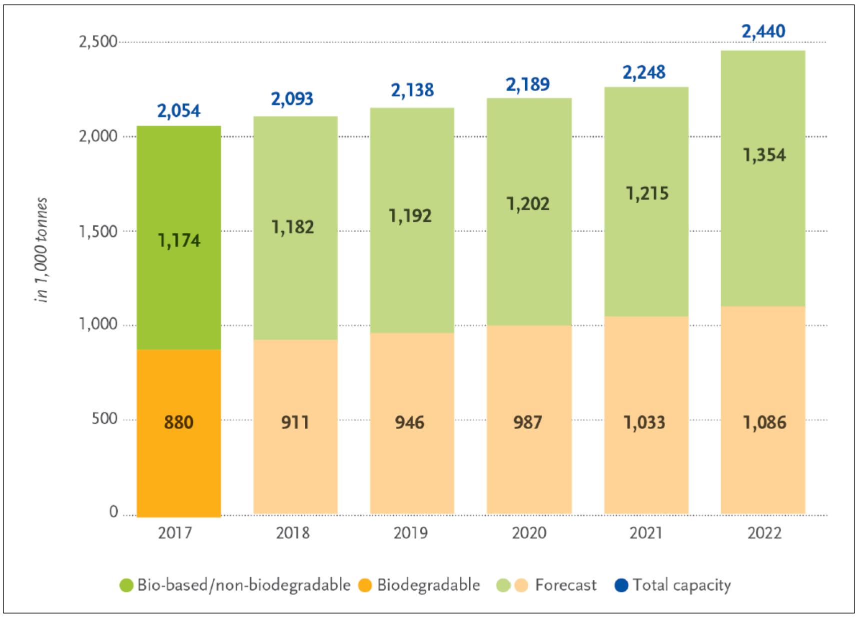


Figure 5 Global production capacities of bioplastics 2017-2022 in 1000 tonnes (Source European Bioplastics)

The geographical distribution of the global plastics production (Figure 2) shows that Europe's production share is significant. Therefore, there is clear space for the expansion of Europe's bio-based industry and the replacement of a significant part of the fossil-based plastics by bioplastics and biopolymers. Data from Plastics Europe (http://www.plasticseurope.org) confirm that packaging is the biggest end-use for plastics (38%), followed by building and construction (21%), automotive (7%), and electrical and electronic (6%). Other applications for plastics, which include medical and leisure, use 28% of the total production volume.

Figure 6 (European Bioplastics 2017) illustrates the global production capacities of bioplastics by market segment. By comparing Table 1 and Figure 6, the market segments absorbing the vast majority of bio-based polymers are (with the exception of the construction sector) the same for the conventional plastics; packaging, textiles and automotive and transport, explained by the significant market drive of increasing volumes. Bio-based PET (20%), PA (25%) and starch-based polymers are produced in the highest volumes.

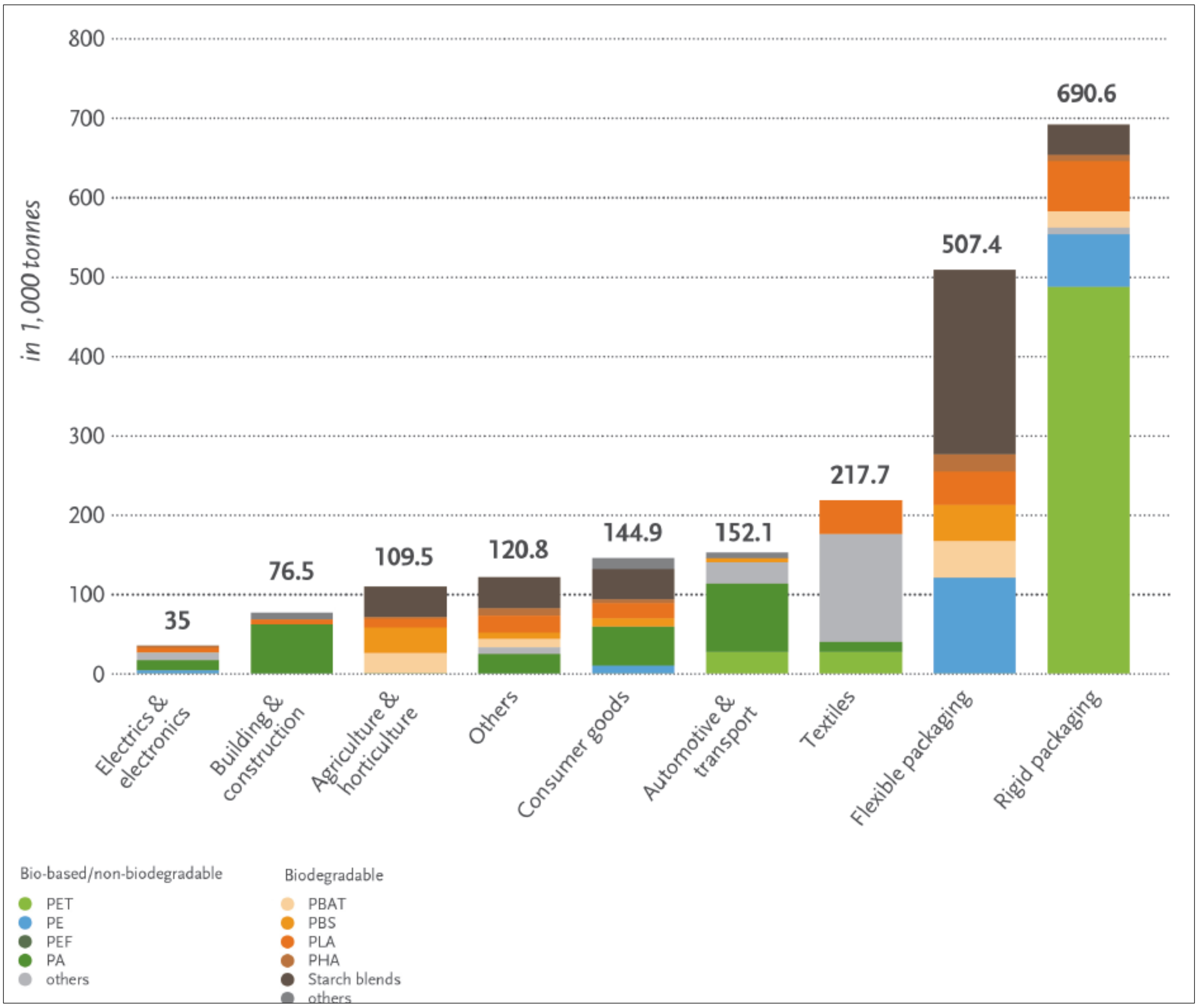


Figure 6 Global production capacities of biodegradable and non-biodegradable bioplastics in 2017 by market segment (European Bioplastics 2017)

3.1.4 Properties and applications of common polymers

The distribution of the plastics consumption along different applications is examined next in further detail. The goal is to identify the corresponding bio-based plastics or polymers having the same properties with fossil-based products and thus being able to replace them in the same industrial or end market applications. Table 1 reports the market share of plastics and polymers of the different market sectors resulting from the combination of data provided by Accenture (Accenture report 2008) and Plastics Europe.

Table 1 Sectoral distribution of global polymer production in 1ooo tonnes

Market sector	2006	Percentage	2016	Percentage
Construction	45886	19%	60766	18%
Plastic products	43500	18%	65302	19%
Food	42025	17%	59812	18%
Textiles	32176	13%	43025	13%
Electrical/electronics	13810	6%	21249	6%

Furniture	13687	6%	19161	6%
Vehicles and parts	10746	4%	13021	4%
Machinery	2397	1%	3048	1%
Fabricated metals	1519	1%	1883	1%
Printing	780	0%	1017	0%
Other transportation	9330	4%	13484	4%
Other equipment	3852	2%	5278	2%
Other manufacturing	21238	9%	27974	8%
Total	240947	100%	335022	100%

The bioplastics will have to compete with conventional polymers in all fronts; properties, supply, economic and environmental sustainability. A list of properties and applications of the most common commercial polymer types is contained in Table 2.

Table 2 Properties and applications of common polymer types

Polymer type	Properties	Applications
PET	Clear and optically smooth surfaces, barrier to oxygen, water and carbon dioxide, heat resistance for hot filling, chemical resistance	Oveneable films and microwave trays, packaging films, industrial and specialty films, and bottles
HDPE	Solvent resistance, higher tensile LDPE films	Grocery bags, cereal box liners, wire and cable coverings, buckets and cheap toys
LDPE	Resistance to acids, bases and vegetable oils, good properties for heat-sealing packaging	Bags for dry cleaning, newspapers, frozen bread, fresh produce and household garbage, shrink wrap and stretch film, coatings for paper milk cartons, and hot and cold beverage cups, wire and cable coverings
PP	Excellent optical clarity in BOPP films, low water vapour transmission, inert to acids, bases and most solvents	Packaging, electronics, kitchen laminates, furniture, ceiling and wall panels, automotive bumpers, dashboards, consoles, door panels etc.
PS	Excellent water barrier for short shelf-life products, good optical clarity, hard wearing	Packaging, electronic housings, medical products, interior furnishing panels
PVC	Biologically and chemically resistant	Packaging films, wire and cable coverings, waterproof clothing, roofing membranes, Building/Construction: pipes, window profiles
PVB	Adheres well to various surfaces, optically clear, tough and flexible	Laminated safety glass for use in automotive and architectural applications

PUR	Thermosetting or thermoplastic, rigid and hard or flexible and soft, solid or cellular with great property variances. Excellent abrasion resistance	Coatings, elastomers and foams

PET = polyethylene terephthalate, HDPE = high-density polyethylene, LDPE = low-density polyethylene, PP = polypropylene, PS = polystyrene, PVC = polyvinyl chloride, PVB = polyvinyl butyral, PUR = polyurethanes

3.1.5 Potential for conventional polymers substitution

According to their origin and method of production, biopolymers are divided into the following three main categories ; i) polymers directly extracted from biomass, ii) polymers classically synthesised from bioderived monomers and iii) polymers produced by microorganisms (Van Tuil et al. 2000). The spectrum of bio-based polymers is schematically summarized in Figure 7 (European Bioplastics 2016).

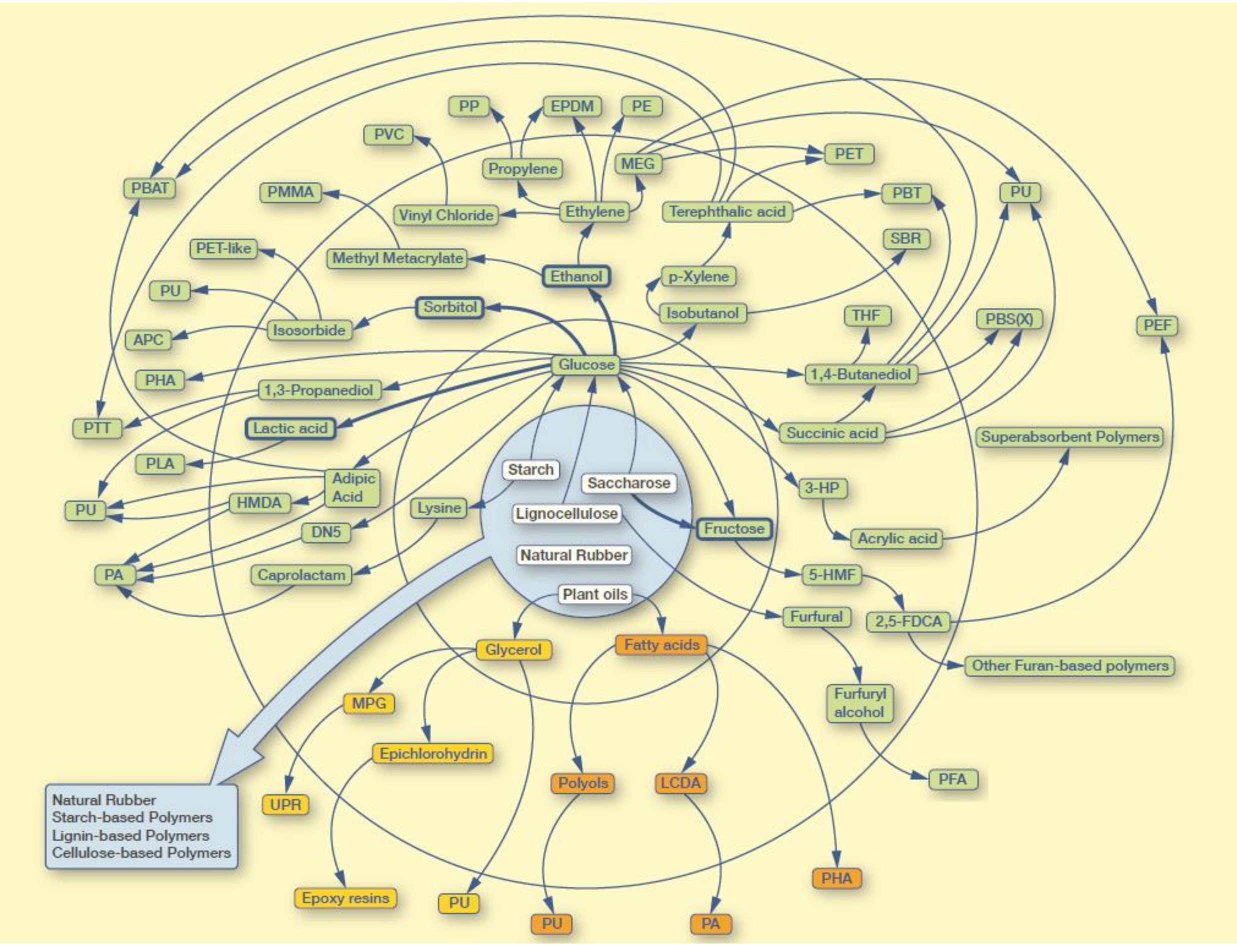


Figure 7 Schematic overview of bio-based polymers based on their origin and method of production.

There is a number of detailed reviews on bio-based polymers and plastics. (Plackett 2011) reports on the chemistry production and applications of starch based-polymers, polylactides, polyhydroxyalkanoates, chitosan, proteins, hemicelluloses, cellulose based materials and furan monomers and polymers. The book of (Kalia and Averous 2016) reports extensively on environmental and biomedical applications of biodegradable and bio-based polymers. A recent review (Nakajima et al. 2017) reports important developments in chemical modifications of naturally derived, bio-engineered and synthetic bio-based polymers and development of new bio-based building blocks for new generation bio-based polymers. The work of (Kalia and Averous 2016) covers almost all the topics related biodegradable and bio-based polymers for environmental and biomedical applications.

Europe is a major hub for the entire bioplastics industry ranking high in the field of research and development and is the industry's largest market worldwide. In Table 3 (Nakajima et al. 2017), the chronological development and categorization of bio-based polymers that are based on application fields are displayed and compared with those of petroleum-derived polymers. From 1970 to 1990, PLA (low L-content) and poly(hydroxyalkanoates) (PHAs) are the most important and representative development of bio-based polymers (Tsuji 2002). During that period, scientists developed a fundamental understanding of bio-based polymers for future applications. Since the 1990s, bio-based polymers have gradually shifted from biodegradable applications to general and engineering applications. High L-content polylactic acid (PLLA), high molecular weight polyhydroxyalkanoates (PHAs), and stereocomplexed-polylactic acid (sc-PLA) (low Tm grade) are important examples of this development. Their derivatives were effectively applied to industrialize general applications of PLLA, PHAs, and succinate polymers. After the successful upgrading of these biodegradable polymers, more promising building blocks have been identified to create more attractive chemical structures for bio-based polymers, which are known as the US Department of Energy's (DOE's) 12 top bio-based molecules (NREL 2004). Around 2010, engineering-grade bio-based polymers that were analogous to petroleum-derived polymers such as poly(ethylene terephthalate) (PET) and polyamides began to be applied to industry. Completely new bio-based polymers with the potential for super-engineering applications also started to appear around 2010. It is expected that these will find new applications and conventional petroleum-derived polymers will lose importance in the long run.

Table 3 Development of bio-based polymers and comparison with petroleum-derived polymers

	Petroleum-derived polymers	**Bio-based polymers**	
	Industry	**Industrial approach**	**Scientific approach**
Super-engineering applications	Since 1960 PEEK, PSU, PES, PPS, PEI, PAI, LCP	not yet	since 2010 bio-LCP, bio-PEEK (new generation)
Engineering/semi-engineering applications	since 1950 Polyamide, POM, PC, PPO, PET, PPT, PBT, ultra-high MW PE, HIPS, specialty nylons	since 2010 bio-PET, bio-PTT, bio-PBT, bio-polyamide (analogous to petroleum-derived ones)	since 2000 polyterpenes, PEF, bio-polyamide, sc-PLA (high Tm), sb-PLA (high Tm) (new generation)
General applications	since 1930 PE, PP, PS, PMMA, PVC, ABS	since 2000 PLLA (high-L content) reinforced PHAs, PHAs blends, succinate polymers, bio-PE/PP	since 1990 sc-PLA (low Tm), PHAs (super high MW), succinate polymers (upgrading from biodegradable polymers)
Biodegradable/biocompatible applications	since 1970 PCL, PEG	since 1990 PLLA (low-L content) PBS (fossil & bio),	since 1970 PLA, PHAs, succinate polymers

	PHAs, PGA, polysaccharides

3.1.6 Value chain stakeholders

Table 4 classifies the identified stakeholders in the European and international area for the biopolymers and bioplastics sector:

Table 4 Stakeholders in the biopolymers and bioplastics sector

Research Organizations	**Producers**	**Services & Equipment**	**Public authorities and development agencies**
Forschungszentrum Julich GmbH University and the Fraunhofer Institute for Molecular Biology and Applied Ecology (IME) - Münster (Fraunhofer IME 2015). - *Rubber from dandelions* VTT Technical Research Centre Of Finland Ltd University Of Pisa Saskatchewan Polytechnic BIOPOLYMERNETWORK	*PLA and PEF* - CORBION BIOPOLYMERS (Corbion 2019) *PEF* – Synvina (Synvina 2019) *Polyamide 12* - Evonic (Evonik 2019) *Limonene, Pinene and Isoprene* - Isobionics (Isobionics 2019) *Polyurethanes, coating and additives* – Covestro (Covestro 2019) *Biobased Adhesives* – Henkel (Henkel 2019), Jowat (Jowat 2019) Biobased peptides – Numaferm (Numaferm 2019) SABIC Limburg B.V. Global Bioenergies Avantium	Thinkstep BRABENDER Polyterra Innovation GmbH	IOWA ECONOMIC DEVELOPMENT AUTHORITY

	SpecialChem Tezkim Tarimsal Kimya Sanayi Ve Ticaret A.S. BP Lenzing Mitsui & Co GmbH Lubrizol Advanced Materials Europe BVBA Rustark Ltd Stora Enso AB Borealis AG Sojitz Europe Plc UNITEDBIOPOLYMERS Rodenburg biopolymers Trinseo Beiersdorf AG Repsol Chemicals NIPPON GOHSEI EUROPE GMBH SunPine AB Allnex Constantia Flexibles Germany Gmbh Draka Polymer Films BV		

	Thyssenkrupp Rasselstein Klaus Dahleke KG IMCD Eastman Chemical Clariant Plastics & Coatings AG		

3.1.7 Conclusions

The biopolymers sector has a great growth potential in Europe and worldwide, and biopolymers are able to substitute fossil-based polymers in almost all industrial and end market applications. A significant property that appears critical is that the biopolymers have to be biodegradable at the same time as been environmentally friendly at their decomposed state. Otherwise, the argument of being derived from natural renewable resources is not eventually supportive.

The current market share of the biopolymers is small, and a significant growth potential is possible provided that significant measures, policies and technological advances will be made. A mix of fossil derived tax, economic incentives and research support will promote the steady growth of the sector.

3.2 PERSPECTIVE STUDY 1 – COATINGS AND PACKAGING MATERIALS

3.2.1 Introduction

The quality and safety of processed food strongly depend on their packaging and the protection that it provides against factors, such as oxygen, nitrogen, CO_2, moisture, microorganisms, temperature etc. Plastics have demonstrated to possess great properties for this. However, the increasing accumulation of synthetic non-biodegradable plastics in the environment represents a threat to the natural habitats. Therefore, the study of the biobased polymers sector's perspective will provide useful insights on the potential of biopolymers to substitute the fossil-based polymers in many applications.

3.2.2 Market status and perspective of biobased coating and packaging material

The European packaging industry has a market value of about 80 billion EUR (Global Packaging Alliance 2011) and accounts for about 40% of the global packaging market. The future trend as it has been the case for the past 30 years, will be towards growing markets on a global scale, while at the same time it is directed towards monolayer packaging that can be recycled, i.e. biodegradable packaging. Packaging products manufactured from renewable materials currently only represent about 2% of the market, traditional fibre-based (i.e. paper) packaging excluded since it is examined in the study of wood products. These factors lead companies and researchers to explore different ways to develop bio-based polymers made from a variety of agricultural commodities and/or food waste products. The newly developed bio-based materials possess performance and functionality features equivalent to or better than petroleum-based materials. Among other applications, a large part of these new materials is intended for coating and packaging applications.

Biologically based packaging is defined as packaging containing raw materials originating from agricultural sources, i.e. produced from renewable, biological raw materials such as starch and bioderived monomers. The marketing of environmentally friendly packaging materials has spurred the creation of numerous projects targeting the development of biodegradable packaging (Petersen et al. 1999). Further to biodegradability, the edibility of food films and coating brings added value to the final product (Anker 1996), although this is a controversial research topic and not a mainstream development. Recently, plant-based polysaccharides such as hemicelluloses and celluloses have attracted attention as replacements for petroleum-based materials (Valdés and Garrigós 2016). The use of cellulose materials as polysaccharides source offers the possibility of obtaining new advanced biomaterials for fresh or processed foods sustainability from the forest sector feedstock (Johansson et al. 2012). Several national and international research projects have been performed in Europe over the last decade, and others are still in progress, with a focus on the potential of bio-materials for replacement of petroleum-derived packaging materials. Examples are the Food Biopack project (BIOPACK 2004), SustainPack (SUSTAINPACK 2008), SustainComp (SUSTAINCOMP 2012), SUNPAP (SUNPAP 2012), FlexPakRenew (FlexPakRenew 2011) and the BBI project HYPERBIOCOAT project (HYPERBIOCOAT 2018).

BIO-BASED INDUSTRIES Public-Private Partnership | Bio-based Industries Consortium | Horizon 2020 European Union Funding for Research & Innovation

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 745719.

According to their origin, biopolymers for coating and packaging applications can be grouped into three main categories (Petersen et al. 1999):

i) Polymers extracted from natural materials such as polysaccharides (e.g. cellulose), lignins, proteins, and lipids.

ii) Polymers produced by chemical synthesis from renewable bioderived monomers (e.g. PLA).

iii) Polymers produced by microorganisms or genetically transformed by bacteria.

Of these biopolymers polylactides (PLAs) have so far made the greatest impact in the marketplace for packaging materials. A considerable amount of research has however been devoted to potential packaging applications for other biopolymers such as starch, PHAs, chitosan, and proteins such as corn zein and gluten.

3.2.3 Properties and standards compliance

The main advantage of biopolymers is their availability from natural resources. However, there is number of challenges in terms of using biopolymers in packaging that include the biodegradability, the edibility in cases, the compostability, processability and final properties such as gas and vapor barriers and finally in compliance with the related standards (see Figure 8).

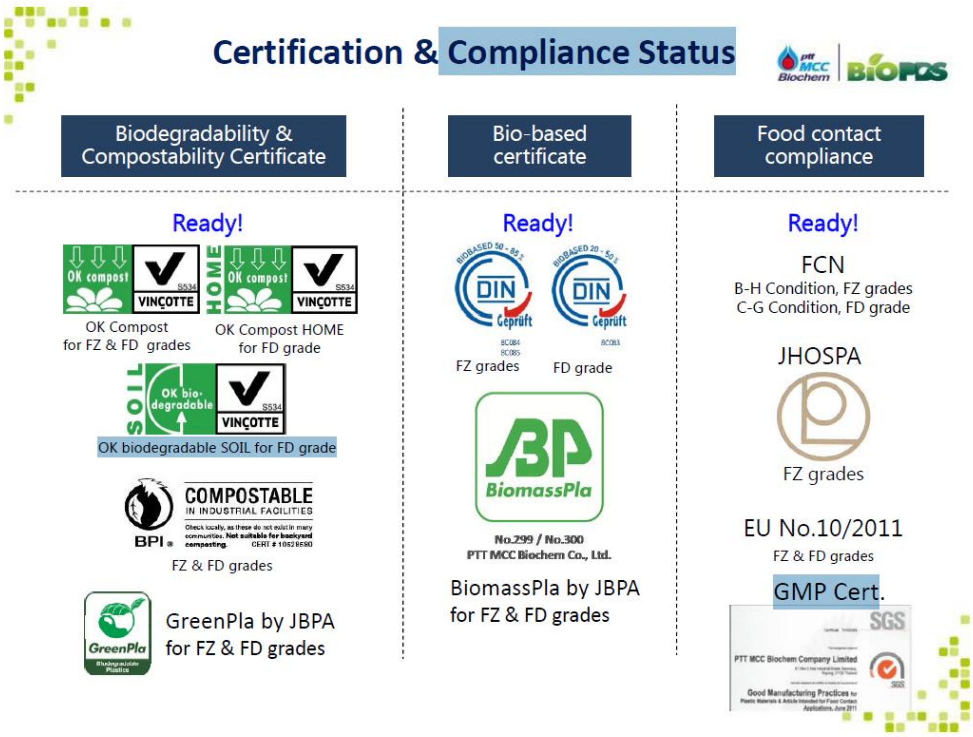


Figure 8 Compostability, bio-based standards and certificates and food contact compliance labels

3.2.4 Innovative processes and products

Selected cases of coatings and packaging materials based on the projects and cluster members of the BIOPEN partners WPCC (Zielona Chemia 2018) are listed below:

1 Antimicrobial coatings of temperature-stable natural substances with antimicrobial properties derived from plants (WPCC)

2 Organic PHA barrier coatings and extruded laminates (WPCC)

3 Tailored edible coating from natural sources with functional components like antimicrobial agents (WPCC)

Next each case is analysed in feedstock, processes, products, applications, business potential and end of life management.

3.2.4.1 Antimicrobial coatings of temperature-stable natural substances with antimicrobial properties derived from plants

Product and application: Antimicrobial coatings of natural substances with antimicrobial properties derived from plants (temperature-stable bio-based antimicrobial agents) (CORNET 2018a).

Description: The shelf-life and safety of food products are often adversely affected by microbial spoiling. The packaging provides protection against contamination after the packing process. Packaging materials that contain antimicrobial agents are able to release these substances onto the surface of the packaged product and so provide additional protection against premature spoiling, i.e. the method of micro-capsulation provides plastics with controlled release of antibacterial substances during food storage (Franhoffer IVV 2018). These antimicrobial agents are either applied to the packaging material surface or are incorporated into the polymer structure of the packaging material (e.g. silver in polypropylene (PP)). From a consumer standpoint, natural substances are preferred. Such natural substances include plant extracts. There is however a lack of knowledge about their suitability for extrusion processes which subject the substances to high temperatures and shear forces and can lead to their decomposition.
Feedstock: Plant material
Production process: Extrusion and micro-encapsulation for additional protection for the active agents
End-of-life: Direct recycle of the packaging material for the same use.

3.2.4.2 Organic PHA barrier coatings and extruded laminates

Product and application: Organic bio-based PHA barrier coatings and extruded laminates for paper and board food packaging (CORNET 2018b). Used for extrusion and lacquering processes for novel applications in paper and board food packaging. In contrast to PET this solution originates from renewable resources and is biodegradable as well. The application field is similar to the use of PET which is widely spread in the flexible packaging market. Containers for cosmetics as well as PHA bottles for water/soft drinks are potentially considered.
Description: Full bio-based coating and laminating solutions
Feedstock: Wastewater from paper mills will be used as a resource to produce these bio-based polymers
Production process: Produce PHAs using

1. Genetically modified microorganisms in a food or paper mill waste glucose rich medium, **or**
2. Usage of mixed cultures of non-modified microorganisms followed by
3. Extrusion

End-of-life: The recycling process can generally be divided into thermal recycling (incineration) and material recycling. Thermal recycling is an option if pure raw materials cannot be recovered like e.g. multilayer films. If the packaging consists of a mono-material structure material recycling is an option.
Relating to the central European waste management system only PET recycling from drinking bottles can be practiced with a sufficient economical plausibility. Based on that role model, PHA recycling could be feasible in a similar way as the material characteristics are comparable. Another promising point is that due to the higher price of the raw material the PHA recycling could be more economical compared to conventional PET recycling. In general, a precondition for an economical recycling is to exceed the

minimum quantity. Due to the insufficient distribution of PHA within the packaging sector these quantities do not exist at the moment. Theoretically, the end-of-life procedures of PHA-coated paper could lead to closing the product life loop in two different ways. First scenario, assuming that PHA (as a raw material) would come from process water in a paper mill, would be transformed in a packaging material and would return to the paper mill after the product have been used and disposed. The material recycling process would close the loop. The second scenario would be assuming that the PHA would be composted and re-used as nutrient to feed raw materials from which paper is produced. Both PHA and cellulose come from nature, therefore the other end of life pathway, considering coming from bio to bio, is to close the loop by bringing the material back to soil or other natural reservoir (PROGRESS 2016).

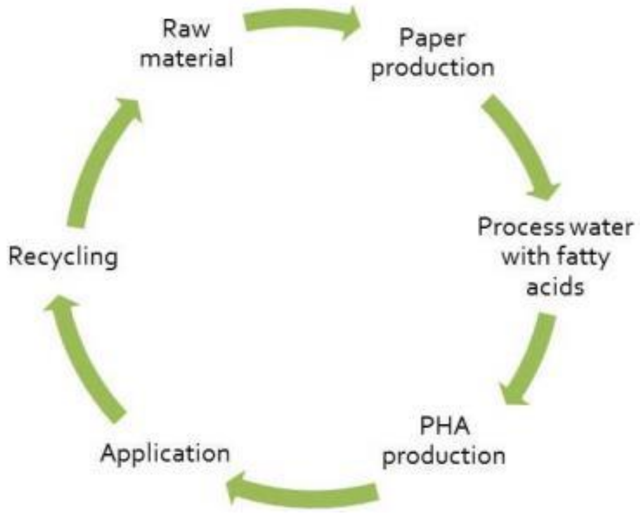


Figure 9 A "closed loop" approach for the development of organic bio-based PHA

3.2.4.3 *Tailored edible coating from natural sources with functional components like antimicrobial agents*

Product and application: Tailored edible coating from natural sources with functional to increase the shelf life, food safety and quality of fresh produce – salad, sprouts, cantaloupes, tropical and local fruits (FreshCoat 2018).

Description: Coating from natural sources with functional components like antimicrobial agents (essential oils, herb extracts), antioxidants (ascorbic acid), texture or nutrient improvers (calcium chloride) in dependency of the specific needs of the selected products.

Feedstock: Edible coatings can be produced from natural sources like carbohydrates or proteins with functional components like antimicrobial agents and antioxidants.

Production process: For the application of the edible coatings on food coating technologies like spraying, dipping or vacuum infiltration can be applied with a focus on industrial feasibility.

Business potential: There is a significant intersectoral business potential for the material, packaging, and retail industry by allowing fresh-cut processors and retailers to innovate their production process and ultimately improve the shelf life and microbial safety of their products. In this way, expanded distribution channels can be established and the amount of food wastage can be decreased. The retail industry will be able to increase their sales areas, the number of clients and annual turnover of fresh-cut fruits and vegetables. Moreover, suppliers of functional ingredients or equipment, packaging machines and materials will benefit from the new developments.

End-of-life: Direct recycle of the packaging material for the same use.

3.2.5 Value chain stakeholders

Table 5 classifies the identified stakeholders in the European and international area for the coatings and packaging materials sector.

Table 5 Stakeholders in the coatings and packaging materials sector

Research Organizations	Producers	Services & Equipment	Public authorities and development agencies
Forschungszentrum Julich GmbH University and the Fraunhofer Institute for Molecular Biology and Applied Ecology (IME) - Münster (Fraunhofer IME 2015). - *Rubber from dandelions* VTT Technical Research Centre Of Finland Ltd University Of Pisa Saskatchewan Polytechnic BIOPOLYMERNETWORK	*PLA and PEF* - CORBION BIOPOLYMERS (Corbion 2019) *PEF* – Synvina (Synvina 2019) *Polyamide 12* - Evonic (Evonik 2019) *Limonene, Pinene and Isoprene* - Isobionics (Isobionics 2019) *Polyurethanes, coating and additives* – Covestro (Covestro 2019) *Biobased Adhesives* – Henkel (Henkel 2019), Jowat (Jowat 2019) Biobased peptides – Numaferm (Numaferm 2019) SABIC Limburg B.V. Global Bioenergies Avantium SpecialChem	Thinkstep BRABENDER Polyterra Innovation GmbH	IOWA ECONOMIC DEVELOPMENT AUTHORITY

	Tezkim Tarimsal Kimya Sanayi Ve Ticaret A.S. BP Lenzing Mitsui & Co GmbH Lubrizol Advanced Materials Europe BVBA Rustark Ltd Stora Enso AB Borealis AG Sojitz Europe Plc UNITEDBIOPOLYMERS Rodenburg biopolymers Trinseo Beiersdorf AG Repsol Chemicals NIPPON GOHSEI EUROPE GMBH SunPine AB Allnex Constantia Flexibles Germany Gmbh Draka Polymer Films BV Thyssenkrupp Rasselstein		

	Klaus Dahleke KG IMCD Eastman Chemical Clariant Plastics & Coatings AG		

3.2.6 Conclusions

The global market trend for biobased coating and packaging material points towards significant growth and it is directed towards mostly monolayer packaging that can be recycled. Among the most important properties for viable biobased packaging material is the biodegradability but mechanical properties and resistance to heat and humidity are equally important. PLA and PHA are the most promising bioproducts for this type of applications.

3.3 PERSPECTIVE STUDY 4 – BIO-AROMATICS FOR SYNTHETIC MATERIALS, CHEMICALS AND COATINGS

3.3.1 Introduction

As a part of global efforts towards CO_2 emissions reduction and the on-going shift towards a bio-based economy, recent developments in the field of aromatics have introduced the bio-based aromatics. Bio-based aromatics – derived from biomass – aim at replacing the traditional building blocks in the chemical industry, and to generate new green blocks with better and more sustainable functionalities. Traditional aromatics such as benzene, toluene, xylene (BTX), are hydrocarbons that are produced from petroleum and in smaller quantities from coal. The application of traditional aromatics, being fossil-based products, creates a heavy dependence on crude oil and has a severe impact on the environment. Bio-based aromatics can serve as a **drop-in** replacement. Moreover, bio-based aromatics may result in **functionalised aromatics,** i.e. new innovative molecules that cannot be derived from petroleum origins. These new chemicals have specific properties that retain as much of the inherent functionality of biomass as possible, are in general better performers and can lead to the development of new applications with enhanced safety, performance and environmental characteristics.

Aromatic molecules represent a very significant share of our today's building blocks, not only in order to create fuel components, base chemicals or polymers, but also to create polymer additives, colorants, flavours and fragrances. Currently virtually all aromatic building blocks are made from fossil oil and thus contribute to large greenhouse gas emissions. Hence, it is important to develop technology to replace the current aromatic petrochemical-based building blocks by alternative feedstocks.

Shale gas and shale oil are rapidly emerging as a new feedstock in the USA but are also fossil in nature and will produce mainly light fractions such as ethylene/propylene, and no aromatics in gas-fuelled crackers. Given the global challenges that society is facing with respect to CO_2 emissions, pollution, global warming and shortage of suitable fossil oil reserves, new bio-based production routes need to be realized urgently to address the ecological and economic challenges that humanity and industry are facing (Biorizon 2018).

Until recently the chemical industry has never had a viable option of technology for producing 100% bio-based basic "drop-in" aromatic chemicals (i.e., BTX) due to the lack of efficient, cost-competitive and scalable processes that utilize biomass feedstocks.

To examine the perspective of the new developments for the production and commercialization of bio-aromatics the present study first analyses the current situation in the aromatics industry and market and then compares it against the offer of the bio-based industry. The study reports on global advancements in bio-aromatics and focuses on the developments within the BIOPEN consortium, further identifying competitive strengths, weaknesses and the needs for supplementary capacities that can be achieved through collaborations and future projects.

3.3.2 The perspective of the general product class of bio-aromatics

What good perspective means is that the production of a specific bio-based product can be profitable and sustainable, i.e. there is a market for it with a sufficient share to justify production in high enough volumes that achieve economies of scale, followed by small production costs. At the same time, the whole purpose of producing bio-based products is to mitigate the environmental impact and reduce the use of fossil non-renewable resources, and by consequence the GHG emissions. The complete life cycle and especially the production process of these bio-based products must have the minimum environmental impact and, in any case, lower than that of the processes producing the conventional fossil-based products. The production of the bio-based products must also have positive socioeconomic effects by producing new high-skilled or technical jobs and by valorizing in the production processes regional and local human and natural resources in a sustainable way.

Several questions have to be answered in order to reach safe conclusions:

1. What is the definition of the conventional products to be replaced?
2. What are the products that bio-based products will replace and in what applications?
3. What is the current volume of conventional products produced and used, and what is the future projection for the consumption of these products?
4. What are the feedstocks for the conventional products and what are the production processes for the conventional products?
5. What are the feedstocks for the bio-based products, and what is the availability of these feedstocks, in terms of quantity, location, and through time?
6. What specifications will the bio-based products have to meet for replacing conventional products?
7. What are the possible **new** applications of the bio-based products?

Modern life produces needs for unprecedented products and applications. The needs for new products can potentially be satisfied directly by bio-based products, without having to pass through the production and use of fossil-based products using conventional processes.

The quick answer to the first and second question is that conventional products to be replaced are Bulk Aromatics: BTX, ethylbenzene, styrene, cumene, phenol, BPA, phthalic acid, isophthalic acid, terephthalic acid phthalic acid anhydride (see Figure 10), with a price range: 600-1500 euro/ton; and specialty aromatics: benzoic acid, hydroxybenzoic acid, mellitic acid, aniline, p-cumyl phenol, resorcinol, catechol etc., with a price range: 1500-3000 euro/ton.

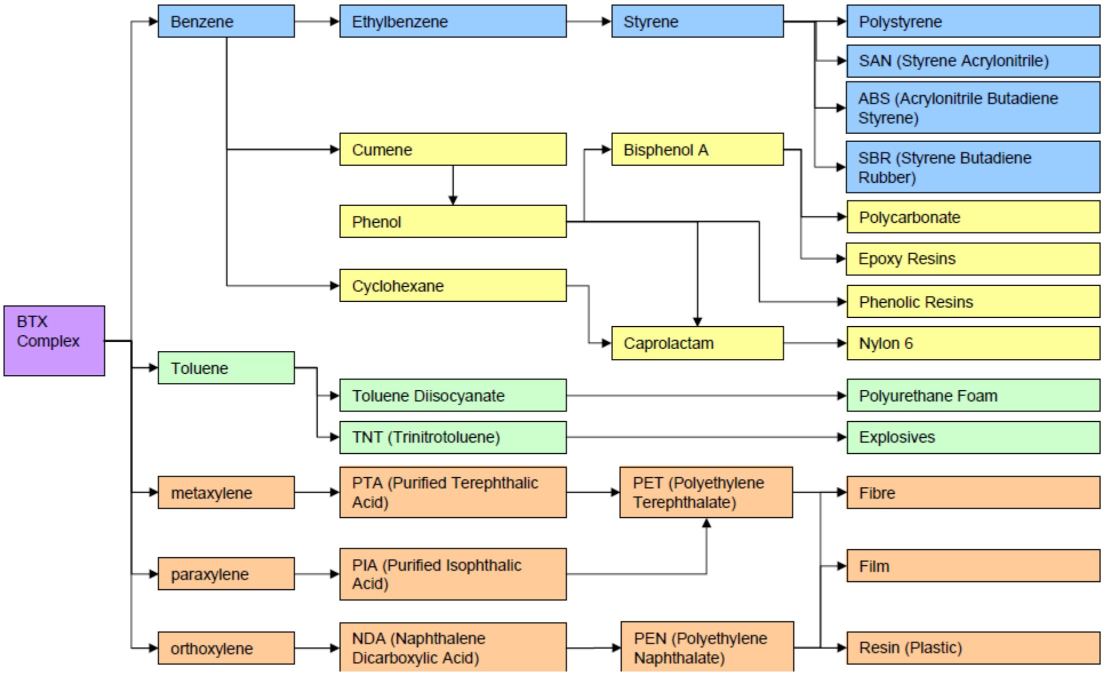


Figure 10 Derivatives and uses of BTX aromatics

For the third question, the current annual production of fossil-based products is 80 million tons, and it grows at 3-4 %.

The feedstock for the conventional products is naphtha (heavy and medium) and the production processes are classical petrochemical processes including cracking, distillation, alkylation etc. (see Figure 11).

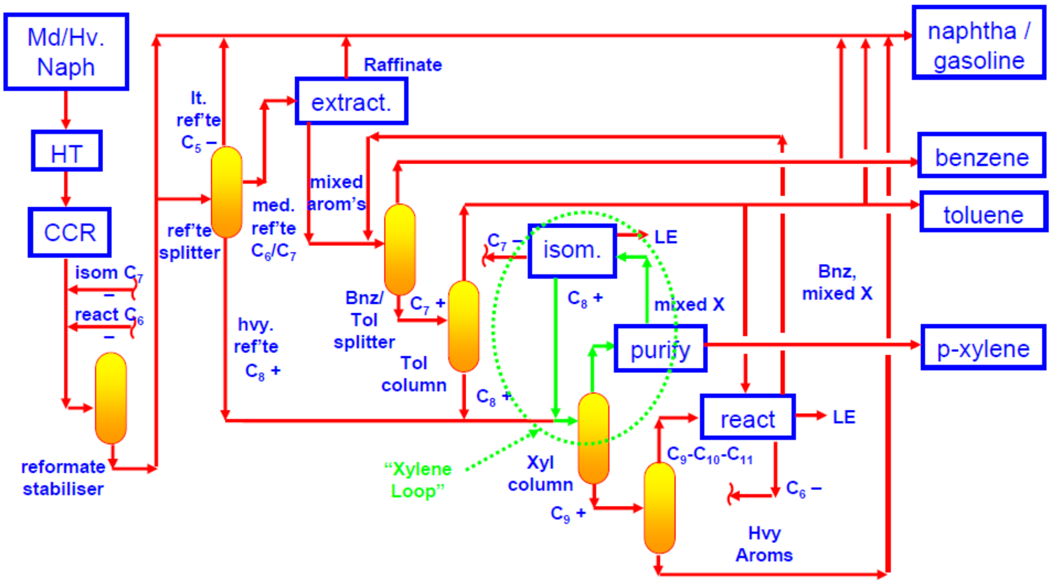


Figure 11 Aromatics plant configuration

The feedstock belongs to a broad range of lignocellulosic material, widely available and growing. IPC studies indicate that 10% of arable land is adequate for the BBE production needs in EU. We need to create this by improving yields and making degrading and degraded lands fertile again. The know-how is available but there is also a need for strong political action and commitment from multiple parties: governments, business, science.

The specifications are the same specs for drop-in chemicals, while new specifications are required for new molecules (also in compliance with the REACH regulation).

3.3.3 Description and properties

From a chemistry perspective it is useful to have a clear image of the structure and properties of aromatics, since we are seeking for platform chemicals derived from biomass that can meet the requirements for such a downstream processing that can lead through the appropriate chemical transformation paths to bio-aromatics.

The general term bio-aromatics is used to describe chemical compounds with similar structure to aromatic compounds (aromatics or arenes), but originating from renewable biomass resources, instead of fossil non-renewable resources. In the traditional sense, aromatics are the chemical substances 'having a chemistry typified by benzene', and in theoretical organic chemistry, a cyclically conjugated molecular entity is said to possess aromatic character when it has stability (due to delocalization) significantly greater than that of a hypothetical localized structure (e.g. Kekulé structure) (IUPAC 2018). Benzene, C_6H_6, is the simplest aromatic hydrocarbon, and it was the first one named as such. Thus, the configuration of six carbon atoms in aromatic compounds is known as a benzene ring. The structure is alternatively illustrated as a circle around the inside of the ring to show six electrons floating around in delocalized molecular orbitals the size of the ring itself (see Figure 12). Aromatic hydrocarbons can be *monocyclic* (MAH) or *polycyclic* (PAH).

Figure 12 Benzene

Some non-benzene-based compounds called **heteroarenes**, are also called aromatic compounds. In these compounds, at least one carbon atom is replaced by one of the heteroatoms oxygen, nitrogen, or sulphur. Examples of non-benzene compounds with aromatic properties are **furan** (Figure 13), a heterocyclic compound with a five-membered ring that includes a single oxygen atom, and pyridine, a heterocyclic compound with a six-membered ring containing one nitrogen atom.

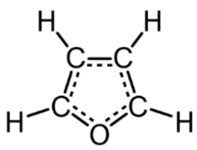


Figure 13 Furan

Furan is of particular interest when discussing the bio-aromatics because, besides the copper-catalysed oxidation of 1,3-butadiene which has fossil origin, it can also be produced via:

1. The thermal decomposition of pentose-containing materials, **and cellulosic solids**, especially pine wood.
2. The palladium-catalyzed decarbonylation of furfural

For the first process, the feedstock is biomass, since pentoses are directly produced by the decomposition (usually hydrolysis) of one of the three main components of lignocellulosic biomass; the hemicellulose (e.g. xylan).

The feedstock for the second process, furfural, may be obtained by the acid catalysed dehydration of 5-carbon sugars (pentoses), particularly xylose (Hoydonckx et al. 2005). Similar to the first process, these sugars may be obtained from hemicellulose present in lignocellulosic biomass, which can be extracted from most terrestrial plants.

Another important and maybe more important component of biomass regarding the production of bio-aromatics is lignin (Lebo et al. 2001). Lignin is a class of complex organic polymers that form important structural materials in the support tissues of vascular plants and some algae. Lignins are particularly important in the formation of cell walls, especially in wood and bark, because they lend rigidity and do not rot easily. Chemically, lignins are cross-linked phenolic polymers (phenolics) (Figure 14). Phenolics is a class of chemical compounds consisting of a hydroxyl group (—OH) bonded directly to an **aromatic** hydrocarbon group. Phenolic compounds are currently synthesized industrially and have significant industrial applications (ex. plastics and wood processing, chemical industry, laboratory processes etc.). Decomposition of lignins for the production of bio-aromatic (mostly phenolic) is a promising alternative to the conventional fossil-based processes.

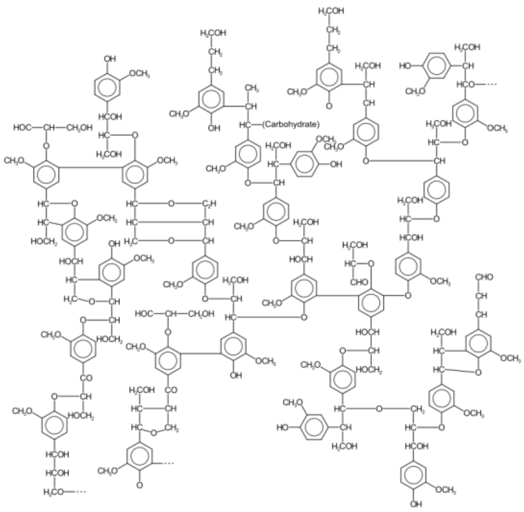


Figure 14 Lignin

The most common among the aromatic compounds that can be produced from lignin are: benzene, toluene and xylene (Figure 15), which in turn are the basic chemicals used in the production of a broad range of chemicals, polymers, and pharmaceuticals.

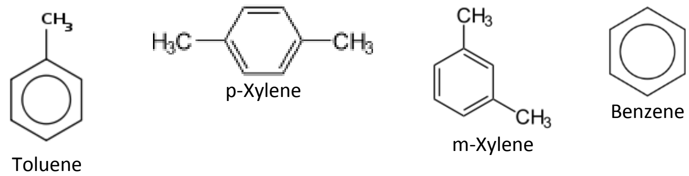


Figure 15 Phenolic compounds that can be produced from lignin

Before discussing the prospects of bio-based aromatics, it is useful to have an overview of the existing market for aromatics produced by conventional processes and from fossil-resources.

3.3.4 Market, applications and end-users of the general aromatics family

In this section we elaborate on the market potential of aromatics in general, and of the four most important aromatics, namely benzene, toluene, xylene and phenol. Aromatics of biological origin are successfully produced and can be used as drop-in chemicals (see Figure 10).

Aromatics

Analysts forecast the global aromatic solvents market to grow at a CAGR of 3.03% during the period 2017-2021 (Technavio 2017). Also, according to (Transparency Market Research 2017) the global aromatic solvents market was valued at US$6.18 billion in 2014 and is projected to expand at a 4.2% CAGR from 2015 to 2023. Growing at this pace, the valuation of the market is anticipated to reach US$7.76 billion by the end of the forecast period (2023). Another independent market study (Credence Research 2016), reports that the aromatic solvents market is expected to reach over US$ 6.50 Bn by 2022, expanding at a CAGR of more than 4.0% from 2016 to 2022.
Geographically, the aromatic solvents market is segmented into Europe, North America, Asia Pacific, the Middle East and Africa (MEA), and Latin America. Of these, Asia Pacific accounted for the major share in 2014, in terms of volume, and the regional market is projected to rise at a spectacular CAGR during the forecast period. The dominance of the regional market is attributed to the rapid growth of the chemicals industry.
The major product segments are benzene, toluene, xylene, and solvent naphtha. Of these, the toluene segment accounted for the major market share in 2014. The demand for toluene is primarily driven by its substantial applications in various industries such as adhesives, paints and coatings, inks, and pharmaceuticals.

Extensive Application of Aromatic Compounds

The aromatic solvents market is primarily driven by the extensive applications of various product segments in the paints and coating industry. The significant rate of solvency of aromatic solvents has popularized their applications in a number of end-use industries such as automotive, pharmaceuticals, and oilfield chemicals (see Figure 10). The extensive application of various aromatic compounds in the paints and coatings industry to speed up the drying process. In addition, these compounds dissolve or disperse a variety of components such as additives, binders, extenders, and pigments, and help in the formation of a homogeneous solution. Hence, they are used by manufacturers in the formulation of paints and coatings, which is a crucial factor boosting the uptake of aromatic solvents.
The growing number of aromatic compounds used in the pharmaceutical and oilfield industries is anticipated to accentuate the market in the coming years. The substantial use of xylene in synthesis of several active pharmaceutical ingredients and in the cleaning of pharmaceutical equipment is anticipated to boost the market. In addition, the use of aromatic solvents in various drug formulation processes is expected to catalyse the market growth.
The extensive application of aromatic solvents as excellent corrosion inhibitors in the oil and gas industry is further expected to boost the market. However, stringent environmental norms and regulations

related to VOC (volatile organic compounds emission) and a gradual industrial shift toward the adoption of non-aromatic solvents are crucial factors likely to hinder the market to an extent. Nevertheless, the burgeoning demand for adhesives and sealants in the automotive sector has boosted the use of aromatic compounds and is expected to catalyse the market world over (Transparency Market Research 2017).

3.3.5 Market status and future perspective of BTX and phenol

3.3.5.1 Benzene

According to (TechSci Research 2015) report, global benzene market is expected to surpass 46MMT by 2020 on account of continuously increasing demand from various industries using benzene derivatives in their manufacturing processes, and it is expected to witness a CAGR of approximately 4.3% during the forecasted period 2017-2021 (Research and Markets 2016) and by 4.3% during the forecasted period 2018-2023 (Mordor Intelligence 2017), majorly driven by growing usage of synthetic polymers, such as polyester and polystyrene in the end-user industries, such as textile, packaging, building & construction, and electrical & electronics .

Ethyl Benzene is expected to dominate the benzene derivative market, owing to its usage in the production of styrene. The rising demand from construction and packaging industry for styrene derivatives is expected to propel the market for benzene. Styrene polymers are used in various applications, like production of synthetic rubbers and expanded polystyrene. Styrene polymers are used in various every day products, like televisions, IT equipment, disposable medical products, like test kits, consumer electronics, like portable speakers, cassette tape housing, etc. Polystyrene in expanded form is used widely in packaging and construction. The growth of these end-user industries, especially in emerging markets, like China, India, and Russia is propelling the growth of styrene, which in turn is responsible for growth in usage of Benzene, as it is one of the key raw materials for styrene production.

Figure 16 presents the global benzene index (source: (Platts S&P Global 2018a)). The most recent known price of benzene is 722.84 €/mt.

Source: S&P Global Platts

Feb-18	Monthly % Change	Annual % Change	Feb-17	Jan-18	Dec-17	Nov-17	Oct-17
$891.30	-2.1%	-10.9%	$1,000.78	$910.56	$910.12	$872.65	$785.52

Figure 16 Global benzene index

3.3.5.2 Toluene

The global toluene market reached a value of US$ 21 Billion in 2016, the market is anticipated to reach a value of more than US$ 28 Billion by 2022, exhibiting a CAGR of 5% during 2017-2022 (Research and Markets 2017a).

The market is expected to be driven by the growing end-user base of toluene and its derivatives in various industries such as, building & construction, automotive, oil & gas, and consumer appliances, among others. The growing petrochemical industry in the Asia-Pacific region countries such as India, Taiwan, and Thailand has also opened new markets for toluene.

The toluene market is segmented by application and derivative; and region. The toluene market can be classified into application and **derivative segments such as, benzene and xylene**; solvents; gasoline additives; TDI; and others such as, trinitrotoluene, benzoic acid, and benzaldehyde. The benzene and xylene segments are projected to be the largest market of toluene due to the growing demand for its derivatives such as, Polystyrene (PS) and Polyethylene Terephthalate (PET) in various applications. This trend is projected to continue due to the increasing automobile and consumer appliances industry in the Asia-Pacific, and Middle Eastern & African regions.

Figure 17 presents the global toluene index (Platts S&P Global 2018a). The most recent known price of toluene is 615.71 €/mt.

Source: S&P Global Platts

Feb-18	Monthly % Change	Annual % Change	Feb-17	Jan-18	Dec-17	Nov-17	Oct-17
$759.20	2.9%	6.4%	$713.81	$738.09	$717.64	$698.42	$672.42

Figure 17 Global toluene index

3.3.5.3 Xylene

The global xylene market is expected to grow at a CAGR of 7.49% (Figure 18) during the period 2017-2021 increasing from 53 to 74 mtpa (Research and Markets 2017b).

Figure 18 Growth of the global xylene market (source: (Technavio 2016)**)**

Global xylene production capacity is poised to see considerable growth over the next nine years, potentially increasing to 81.1 mtpa in 2026. Around 35 planned and announced projects are slated to come online in the next nine years, primarily in Asia and the Middle East. In Asia, China has nine planned and announced xylene projects, with a total capacity of about 9.3 mtpa by 2020 with capex for these projects being close to US$7.55 billion (Research and Markets 2017c).

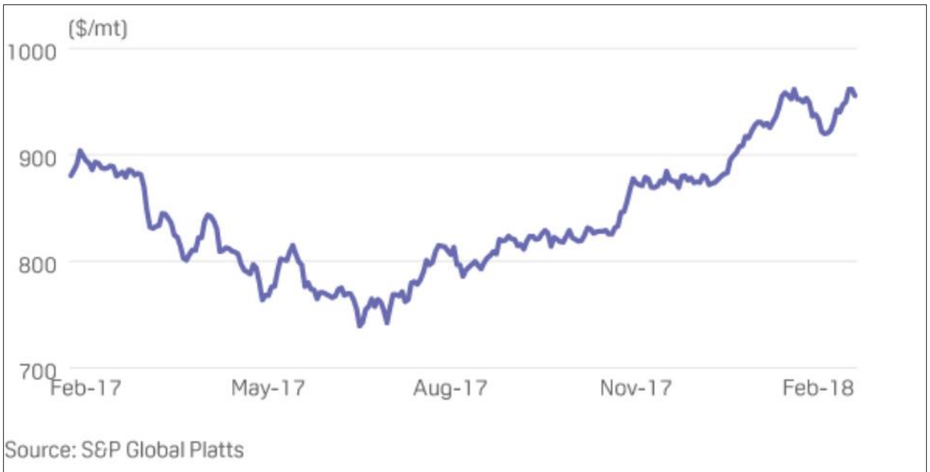
In the Middle East, Iran has four planned and announced xylene projects, expected to start operations with a total capacity of about 1.5 mtpa by 2021. Capital expenditure (capex) for these projects totals US$1.33 billion over the next nine years.

In the Former Soviet Union, majority of xylene capacity additions are in Russia, with capacity of about 0.3 mtpa by 2018. Whereas, in Europe, Spain plans to spend US$0.04 billion and add a capacity of 0.07 mtpa, expected to come on-stream by 2018.

Growing polymer and petrochemical sector coupled with increasing demand for PET, leather and rubber are expected to drive xylene market over the next six years (Grand View Research 2014). In addition, increasing use of polyesters in textile industry is anticipated to augment the xylene market growth over the forecast period. Favourable government regulations supporting bio-based chemicals in agriculture is expected to hamper the market demand in the next six years. Uncertain raw material supply resulting in price volatility is expected to act as a market restraint over the forecast period. Technological advancements regarding xylene’s use as a solvent in medical industry are poised to create growth avenues.

Rising xylene demand owing to increasing applications in major industries including leather and rubber especially in Asia Pacific and the Middle East are expected to drive global market over the forecast period. Shift in xylene manufacturing bases from Europe and North America to emerging economies of India and China owing to availability of inexpensive labour is expected to fuel Asia Pacific market growth over the next six years. Furthermore, China is anticipated to be major consumer for xylene on account of growing demand for pesticides in agricultural sector over the forecast period. Major applications of xylene include pure terephthalic acid (PTA) production; paint, dyes & pigments and for laboratory use. In the form of p-xylene it is also used in the manufacture of PTA (purified terephthalic acid), which is a basic petrochemical used in the textile industry for making polyester. North America and Europe are expected to witness below average growth rates owing to slowdown in end-use market demand for PET over the next six years. Xylene isomers can be segmented as o-xylene, p-xylene and m-xylene for use in foams, adhesives and films. Ortho-xylene in particular is used extensively for producing phthalic anhydride (PAN)-primarily dio-octyl phthalate for PVC. The major use for PAN is for producing plasticizers which are largely used in automobile and construction industry. In addition, it is used in solvent based paints.

Figure 19 presents the global p-xylene index (Platts S&P Global 2018a). The most recent known price of paraxylene is 763.03 €/mt.



Feb-18	Monthly % Change	Annual % Change	Feb-17	Jan-18	Dec-17	Nov-17	Oct-17
$940.85	0.6%	5.9%	$888.80	$935.52	$880.96	$870.49	$825.46

Figure 19 Global p-xylene index

3.3.5.4 Phenol

The global phenol output rates declined during the recession, but they returned to normality in 2010. From 2010 to 2012, the world phenol production registered positive annual growth (nearly 2.5%), increasing from 8.34 million tonnes in 2010 to more than 8.9 million tonnes in 2012. APAC was the world's unrivalled leader in phenol production, accounting for over 41% (above 3.7 million tonnes) of the overall output volume. China, the USA, Japan, Taiwan and South Korea were the top five phenol manufacturing countries in 2012 with a combined production of more than 5.5 million tonnes in volume. In 2012, global annual production capacity of phenol was estimated at over 11.5 million tonnes. In the same year, APAC held over 41% of the world estimated capacity. It was followed by Europe and North America. During 2010-2012, the world phenol consumption followed an upward trend, and in 2012, it surpassed the 8.9 million tonnes mark. In 2012, APAC was the dominant phenol consumer, accounting for over 46% of the global phenol consumption in volume terms. In the same year, the Bisphenol A industry was the major phenol end-use sector. The global phenol foreign trade exceeded USD 3.6 billion in 2012 (> 404$/t). Europe was the leading phenol exporter and importer (Merchant Research and Consulting ltd. 2014). Table 6 reports past and projected capacities for the global production of phenol. Over the period 2018-

2020, it is forecasted (ICIS Consulting 2016) that the global demand for phenol to increase at an average of around 3% per year, with Asia and South America driving the growth in demand.

Table 6 Annual capacity of phenol production

Year	Phenol Capacity (mtpa)
2015	12.6
2016	13.1
2017	13.4
2018 (E)	13.7

The global demand pattern for phenol in 2015 is shown in Figure 20.

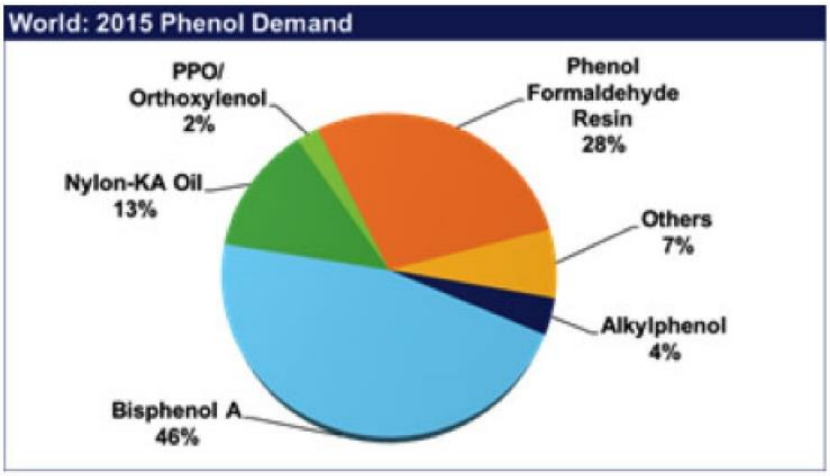


Figure 20 Global phenol demand for 2015 (source: (Plotkin 2016))

The largest end-use for phenol is in the manufacture of bisphenol A (BPA). Although it is under regulatory pressure for health and safety reasons, BPA is the key building block for making polycarbonate and epoxy resins. The next largest use for phenol is in the production of phenol–formaldehyde (PF) resins. PF resins are used primarily in wood adhesives, for example, for bonding the layers of plies in exterior plywood.

The most recent price of phenol in 2018: 1264.70 €/t. Past and recent prices of phenol are reported in Figure 21 and Figure 22.

Figure 21 Price of phenol (source: ICIS)

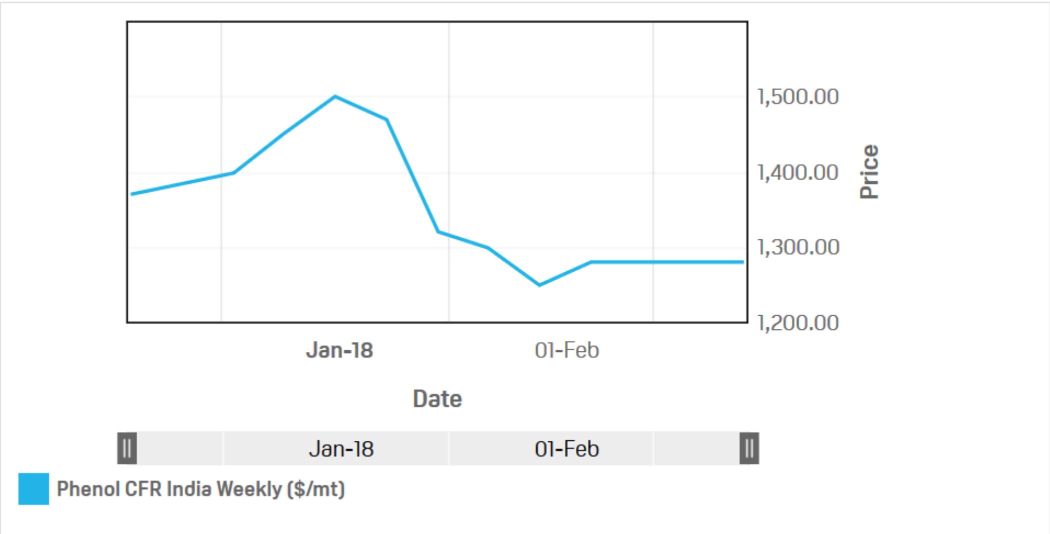


Figure 22 Recent prices of phenol (source: (Platts S&P Global 2018b)**)**

3.3.6 The bio-aromatics value chain

The current section describes the bio-aromatics value chain and its key stakeholders and relationships. In EU it has not taken off essentially from the R&D stage.

Feedstock

Biomass that is used for the production of bio-based aromatics can be derived from various feedstocks. At the moment, most R&D in the EU concentrate on lignocellulosic (LC) biomass, referring to plant biomass that is composed of cellulose, hemicellulose, and lignin (BIOCORE 2014).

The analytical report of the KETs observatory on bio-aromatics (KET Observatory 2018), uses three dimensions to represents the value chain structure for bio-based aromatics; value-adding activities; supply chain[4]; and enablers (see Figure 23).

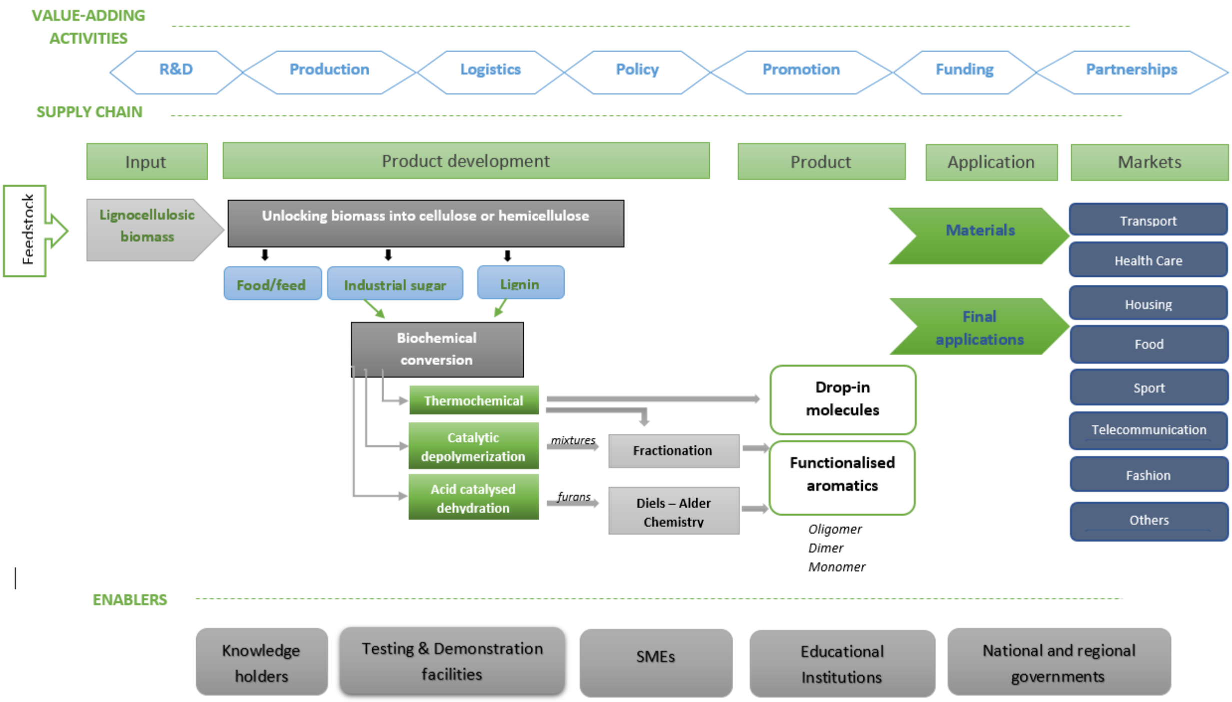


Figure 23 Value chain for bio-based aromatics - based on: (Biorizon 2015; Deloitte 2015)

The first dimension includes value-adding activities; research for technology development and business uptake; promotion; national and EU policies; access to funding; partnerships; production and logistics infrastructures.

The second layer represents the main supply chain processes. Bio-based aromatics production technology uses lignocellulosic biomass as the main source of feedstock. Table 7 shows the main feedstock supply for LC biomass[5].

Table 7 Feedstock for lignocellulosic biomass (BIOCORE 2014)

Origin of the feedstock	Type of feedstock
Agricultural supply	Straw, grain, chaff, cobs, starch or bagasse
Forestry supply and residues	Wood, branches, foliage, roots
Bio-waste streams	Municipal solid waste, food processing waste

[4] The biochemical processes mentioned in Figure 24 are not exhaustive and are based on the process applied in Biorizon Shared Research Centre

[5] The presented list should not be considered exhaustive.

The feedstock is first decomposed into the main lignocellulosic biomass components; cellulose, hemicellulose and lignin, which then undergo a series of series or common chemical, thermochemical and biochemical processes before being finally converted into drop-in chemicals or being further processes to produce functionalized bio-aromatics.

The technology readiness level (TRL) of the functionalised aromatic products differs from case to case. Biorizon (Biorizon 2018) - for example - plans to realize a 40 ton/year scale in 2020 by reaching 5th and 6th levels of the technology readiness. It expects to commercialise its production by 2025 (KET Observatory 2018).

The application scope of bio-based aromatics is extensive, ranging from inks, paints, tires, textile, wood panels and laminates, glues, adhesives, polymers (polyesters, polyurethanes, polycarbonates, polyamides etc.), emulsifiers, coatings, fragrances and aromas, pharma and fine chemicals.

The third dimension consists of knowledge transfer and technology developments enablers, which include research and technology organizations (universities, institutes), infrastructure providers for testing optimizing and demonstrating technologies, and governmental bodies that will follow and support the progress by issuing policies that incentivise and facilitate the development of the bio-aromatics value chains, giving also motivation and enable the broad participation of SMEs.

3.3.7 Global advancements in the bio-aromatics industry

Globally, there are already several successful initiatives for the commercial scale production of bio-aromatics; in the USA three bio-aromatics production processes are already either commercialized (Tullo 2016a; Focus on Catalysts 2017) or are being tested at pilot scale (CHEMICALS Technology 2018).

Anellotech (Anellotech 2018) has developed a one-reactor thermal (pyrolysis) catalytic process (TCat-8) for converting non-food biomass into aromatics. Anellotech's technology is based on the work of George W. Huber, conducted at the department of chemical engineering at University of Massachusetts, Amherst (Carlson et al. 2011). Feedstock includes wood (pine, palm trunks), corn stover and sugarcane bagasse, sawdust and old newsprint. The catalytic fast pyrolysis begins with pyrolysis of the solid biomass into anhydrosugars followed by dehydration to form furanic compounds as shown in Figure 24. These oxygenated species then enter the zeolite pores, undergoing a series of dehydration, decarbonylation and oligomerization reactions to form aromatics, olefins, CO, CO_2 and water. Coke is formed from several routes including homogeneous decomposition reactions of the oxygenates and catalytic reactions inside the zeolite. Production of the desired aromatics is achieved by: (1) proper catalyst selection, (2) high heating rates to avoid unwanted thermal decomposition reactions, and (3) working at high catalyst to feed ratios (Carlson et al. 2011).

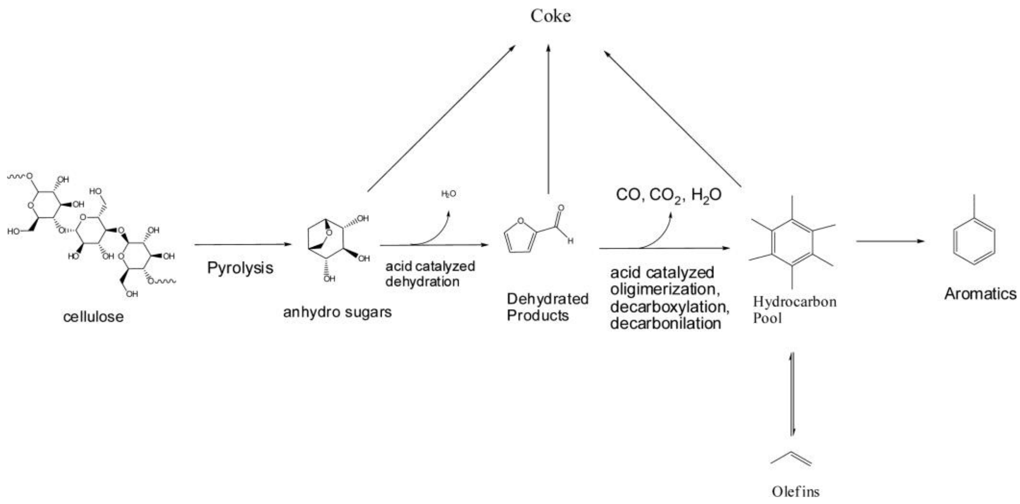


Figure 24 Reaction Scheme for Catalytic Fast Pyrolysis of the TCat-8 process

The bio-based products, chemically identical to petroleum-based aromatics, are used to make important plastics such as polyester (polyethylene terephthalate or “PET”), polystyrenes, polycarbonates, nylons and polyurethanes that ultimately are transformed into consumer goods such as beverage bottles, food packaging, clothing, footwear, carpeting, automotive and electronic components, and more.

Anellotech has started in 2018 a process development and testing programme at its TCat-8 pilot plant in the US to confirm process economics and collect data for commercial design. The process yields 0.5 tons of product for every 2 tons of feedstock (Tullo 2016b) and plant is producing test samples of bio-based renewable aromatic chemicals for conversion by third-parties into bio-based polymer prototypes.

In 2014 Virent (Virent 2018) patented BioForming® technology (Figure 25), which enables the production of many polymers from bio-based feedstocks (Blommel et al. 2014). BioForming® produces the foundational chemicals that are the building blocks of polyesters, polyurethanes, polycarbonates, synthetic rubbers, polystyrene, nylon and more. In addition, these bio-based chemicals have other wide-ranging non-polymer uses in solvents, dyes, food preservatives, detergents and pharmaceuticals. Already from 2015, Virent runs its BTX demonstration production plant with Aromatics output: ~35k – 40k L/yr (25-30T/yr) and purification of mixed xylenes to 99.7+% para-xylene at a >500 kg/month bio PX production and has demonstrated in collaboration with Coca Cola PET bottles from bio-PX (BiofuelsDigest 2015). Virent’s process can convert conventional feedstocks (beet sugar, sugar cane, corn starch) as well as next generation cellulosic feedstocks (bagasse, corn stover, grasses, sorghum and wood).

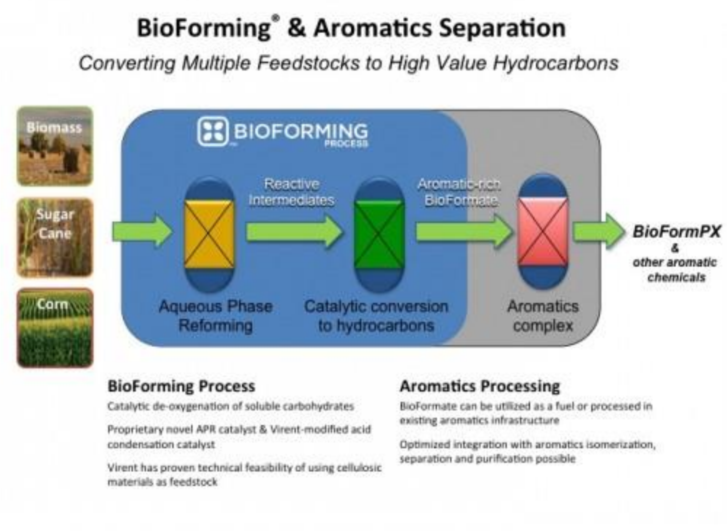


Figure 25 Virent's BIOFORMING process

In 2011, Gevo, Inc. (Gevo 2018) , a company specialising in the production and subsequent conversion of bio-based isobutanol, patented a process for the production of p-xylene from isobutanol (Peters et al. 2011). A schematic overview of this process is depicted in Figure 26. Isobutanol is first obtained via conversion from glucose (derived from the saccharification of starch) using metabolically engineered microorganisms. Isobutanol then undergoes subsequent dehydration (at 265 ^{o}C and 50.83 bar) to isobutene over g-Al2O3. The H-ZSM-5-catalysed oligomerisation of the obtained isobutene (45 ^{o}C, 52.01 bar) affords iso-octene, which is finally dehydrocyclised at 525 8C and 1.38 bar to yield p-xylene using a commercial chromium-oxide catalyst (BASF-1145E) (Maneffa et al. 2016). Dodds and Humphreys reported that the complete process yields 18.7 kg p-xylene per 100 kg glucose (Dodds and Humphreys 2013). Gevo's route from isobutanol has already been commercialised within the biorefinery in Silsbee, Texas, U.S.A. in collaboration with South Hampton Resources Inc (Business Wire 2011) and a capacity of 40 mtpa of isobutanol processing (GEVO News Releases 2011) and it is already selling para-xylene (PX) derived from its renewable isobutanol to Toray, one of the world's leading producers of PET for fibers, plastics, films, and chemicals (Bioplastics Magazine 2014; GEVO News Releases 2014).

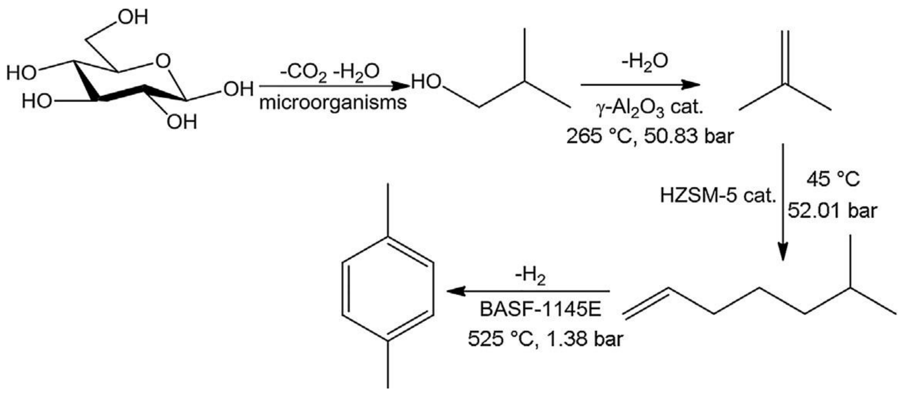


Figure 26 Gevo Inc. process for converting isobutanol (from glucose) to p-xylene. BASF-1145E is the commercial chromium-oxide catalyst.

In Europe Avantium (Avantium 2018) produces bio-based PEF, which is itself a polyester-based on FDCA and MEG (ethylene-glycol), and is used to create bottles, films and fibers. The polymerization process to make PEF has already been successfully initiated at pilot plant scale and Avantium is currently evaluating the process of Furanics-based polyamides with several industrial partners. PEF is a next-generation polyester PEF that offers superior barrier and thermal properties, making it ideal material for the packaging of soft drinks, water, alcoholic beverages, fruit juices, food and non-food products. Therefore, PEF is the 100% bio-based alternative to PET. Currently, Avantium is working in collaboration with The Coca Cola Company, Danone and ALPLA to bring 100% bio-based PEF bottles to the market.

3.3.8 The European perspective - Initiatives within and outside the BIOPEN consortium

The discovery of new routes and approaches for the production and commercialization of bio-aromatics is one of the key priorities of the BIOPEN project partners. Part of Bio Based Delta (BBD) (Biobaseddelta 2018) is the Biorizon Shared Research Center (Biorizon 2018) focusing on technology development for the production of bio-based bulkaromatics (BTX) and functionalized bio-based aromatics for performance materials, chemicals & coatings. Biorizon is anticipating the expected growing shortage of aromatics from the petrochemical industry and the widely shared ambition to green the chemical industry. The compound annual growth rates (CAGRs) reported in the previous section for the markets of benzene, toluene, xylene and phenol for the years up to 2022, justify this expectation. However, the fluctuation of the prices of these conventionally fossil-based chemicals raises a concern regarding the possibility of the bio-processes to compete in economic terms, especially when – as in current times – the prices (of phenol for example) are being directly attached to the falling prices of oil and gas. In the broad European region most initiatives regarding the production and commercialization of bio-aromatics are in effect represented by undergoing or completed projects within the framework of Biorizon (Biorizon 2018).

To enable commercial production of bio-aromatics by 2025, Biorizon developed a roadmap consisting of 3 program lines, referred to as “horizons”, each starting with an R&D phase including lab, bench and pilot phases with the goal of eventually demonstrating techno-economic viability are relevant scale.

The three horizons of the Biorizon roadmap are:

1. Thermo-chemical: focus on the development of (catalytic) thermo-chemical technologies (e.g. gasification, pyrolysis) for BTX production and production of functionalized aromatics from low-cost biomass and biomass fractions.
2. Sugar/furan: focus on the development of (bio-)chemical technologies toward functionalized drop-in (bulk) aromatics from sugar.
3. Lignin: focus on the development of (bio-)chemical technologies toward (mixtures of) functionalized aromatic compounds (oligomers, dimers, monomers) from lignin.

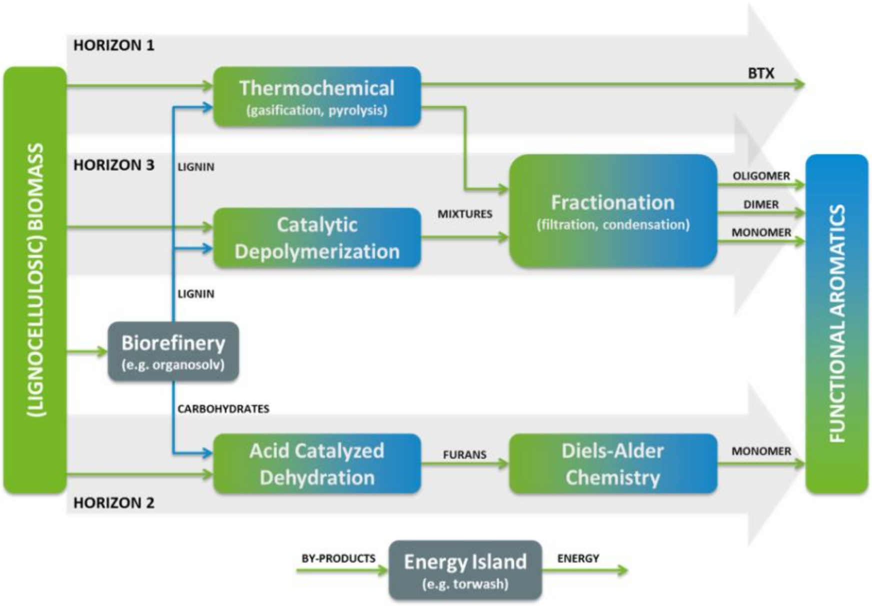


Figure 27 The three horizons of the Biorizon's roadmap

Table 8 lists selected projects linked to BIORIZON working on the production of aromatics from green raw materials, with end-uses in the production of synthetic materials, chemicals and coatings like paint and glue.

Table 8 List of BIORIZON linked projects on the production and applications of bio-based aromatics

No	Project
1	LigniOx: Lignin oxidation technology for versatile lignin dispersants
2	BIO-HArT: Biorizon Innovation and Upscaling of Renewable Aromatics Technology
3	Waste2Aromatics
4	ARBOREF: Biorefinery of entire plant biomass to aromatics
5	SCeLiO-4B: Sugars, Celluloses and Lignin Scaling up towards Bio-based Building Blocks
6	MAIA: Manufacturing of Advanced and Innovative bio-Aromatics
7	SmartLi
8	From lignin to new (bio)chemicals

The goals and current results of the Biorizon projects are described below.

1. **LigniOx** (LigniOx 2018): The aim of the LigniOx Innovation Action is to demonstrate the techno-economic viability of alkali-O2 oxidation technology (LigniOx) for the conversion of variable lignin-rich side-streams into versatile dispersants, and especially high-performance concrete and mortar plasticizers.
   The versatile LigniOx technology can be integrated into lignocellulosic biorefineries or be operated as a stand-alone unit by chemical industry, as demonstrated in the project.
2. **BIO-HArT** (BIO-HArT 2018) aims at realizing generic and multi-purpose bench scale demonstrators for 3 technologies (see Figure 28: wood, sugars and lignin to aromatics) and the production of samples of sugars, lignin, furans, akylphenols, mono-, di- & tri-acids, functionalized phenols and other aromatic compounds, further developing industrial applications for the products at hand .

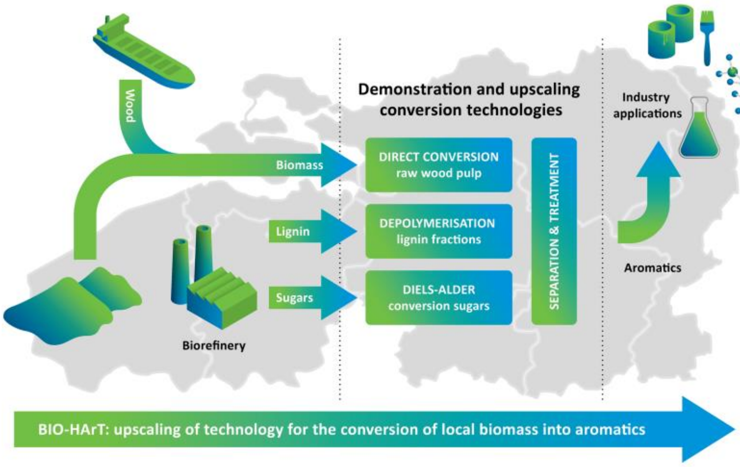


Figure 28 A visual impression of the BIO-HArT project

3. **Waste2Aromatics** investigates how carbohydrates (sugars) in municipal waste streams can be used as a source for the production of bio-based aromatics. In order to produce bio-aromatics from municipal waste streams, the (hemi-) cellulose that is present in the organic fractions is transformed into furans using two different technologies; the superheated steam (SHS) technology suitable mainly for processing relatively solid material using steam to remove furans from the waste stream and a two-fluid phase system where furans are extracted using an organic solvent. In both cases furans are the basic intermediate for the production of aromatics see Figure 29 (Waste2Aromatics).

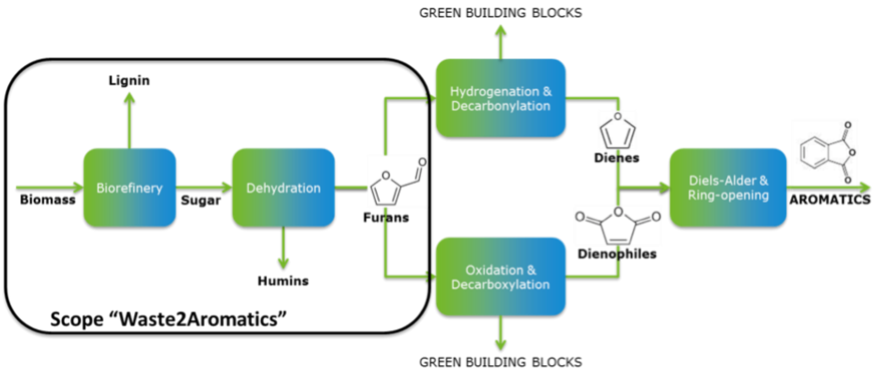


Figure 29 The 'Sugars to Aromatics' of the Waste2Aromatics project

4. **Arboref** aspires to develop a timber bio-refinery for aromatics with 90% carbon efficiency, adopting a recently developed technology, which converts wood into high yields of mono-phenols (from lignin), and a fixed (hemi) cellulose pulp. Useful aromatics will be produced from both fractions in this project. On the one hand, the phenols are reduced to building blocks that can be used in the polyurethane, polyester, polyamide, polycarbonate and phenol resin industry. On the other hand, the sugar pulp is also used for the production of aromatics such as benzene, styrene, and terephthalic acid (Arboref 2018).
5. **SCeLiO-4B** conducts research on the depolymerization of lignin and on the use of furfural and HMF as platform chemicals toward drop-in dienes and dienophile chemicals and compounds with new functionality, suitable for producing bio-based aromatic chemicals. Examples of dienes include (substituted) furans and 5-hydroxymethylfurfuran (5-HMF); and for dienophiles, maleic acid anhydride and acrylic acid ester (SCeLiO-4B 2018).
6. **MAIA** aims at the development of an innovative industrial process for conversion of residual waste wood and flax co-products into bio-aromatics. The waste wood and flax shive refinery will be fine-tuned in function of several selected applications represented by different industrial partners, such

as dispersion agents and emulsifiers, resins for ink, foundry, refractory and wood modification, wood adhesives, UV-stabilizers and flavours (MAIA 2018).

7. **SmartLi** aims at developing technologies for using technical lignins as raw materials for biomaterials and demonstrating their industrial feasibility. The technical lignins included in the study are kraft lignins, lignosulphonates and bleaching effluents, representing all types of abundant lignin sources. The raw materials are obtained from industrial partners. The technical lignins are not directly applicable for the production of biomaterials with acceptable product specifications. Therefore, pre-treatments will be developed to reduce their sulphur content and odour and provide constant quality. Thermal pre-treatments are also expected to improve the material properties of lignin to be used as reinforcing filler in composites, while fractionating pre-treatments will provide streams that will be tested as plasticizers.
   Lignin is expected to add value to composites also by improving their flame retardancy. The development of composite applications is led by an industrial partner. Base catalysed degradation will be studied as means to yield reactive oligomeric lignin fractions for resin applications. The degradation will be followed by downstream processing and potentially by further chemical modification aiming at a polyol replacement in PU resins. Also, PF type resins for gluing and laminate impregnation, and epoxy resins will be among the target products (SmartLi 2018).
8. **From lignin to new (bio)chemicals** aims to accelerate the development of functional bio-aromatic chemicals from tree lignin, which is a natural source of highly functional aromatic units. The project aims at developing technologies for splitting the strong lignin structure in the right places to retain the chemically interesting building blocks, for then separating the different components from the lignin 'soup' and lastly, for turning the new bioaromatic molecules into high value products (Biorizon-projects 2018).

3.3.9 Value chain stakeholders

The following key actors are identified across the value chain: biomass suppliers for the provision of feedstock, R&C organizations for the development of innovative technologies, parties managing the supply chain, biorefineries separating and converting raw materials for industrial use (De Jong and Jungmeier 2015), industries converting the intermediates to products and commercial brand owners specifying the products for consumers. While biomass can be imported at the world market prices, Europe has all the necessary conditions to make the conversions at home (European Commission 2013).

The following stakeholders are identified in the European and international area of bioaromatics:
US: Anellotech (Anellotech 2018), Virent (Virent 2018) and , Gevo, Inc. (Gevo 2018)
Europe: Avantium (Avantium 2018)

Also all project partners of:
Concrete and mortar plasticizers **- LigniOx** (LigniOx 2018)
Sugars, lignin, furans, akylphenols, mono-, di- & tri-acids, functionalized phenols - **BIO-HArT** (BIO-HArT 2018)
Furans and aromatics - **Waste2Aromatics** (Waste2Aromatics 2018)
Benzene, styrene, and terephthalic acid - **Arboref** (Arboref 2018)
Furfural and 5-hydroxymethylfurfuran (5-HMF), dienes and dienophiles (maleic acid anhydride and acrylic acid ester) - **SCeLiO-4B** (SCeLiO-4B 2018)
Bio-aromatics for dispersion agents and emulsifiers, resins for ink, foundry, refractory and wood modification, wood adhesives, UV-stabilizers and flavours - **MAIA** (MAIA 2018)

Lignin for polyol replacement in PU resins and PF type resins for gluing and laminate impregnation, and epoxy resins - **SmartLi** (SmartLi 2018)
Bio-aromatics - Project partners of "**From lignin (bio)chemicals"** (Biorizon-projects 2018).
The following table reports an extended list of stakeholders related to the product and other sectors:

Table 9 Extended list of stakeholders in the bioaromatics sector

Research Organizations	**Producers using bioaromatics as feedstock**	**Services & Equipment**	**Public authorities and development agencies**
Forschungszentrum Julich GmbH University and the Fraunhofer Institute for Molecular Biology and Applied Ecology (IME) - Münster (Fraunhofer IME 2015). - *Rubber from dandelions* VTT Technical Research Centre Of Finland Ltd University Of Pisa Saskatchewan Polytechnic BIOPOLYMERNETWORK	SABIC Limburg B.V. Global Bioenergies Avantium SpecialChem Tezkim Tarimsal Kimya Sanayi Ve Ticaret A.S. BP Lenzing Mitsui & Co GmbH Lubrizol Advanced Materials Europe BVBA Rustark Ltd Stora Enso AB Borealis AG Sojitz Europe Plc UNITEDBIOPOLYMERS Rodenburg biopolymers Trinseo	Thinkstep BRABENDER Polyterra Innovation GmbH	IOWA ECONOMIC DEVELOPMENT AUTHORITY

	Beiersdorf AG Repsol Chemicals NIPPON GOHSEI EUROPE GMBH SunPine AB Allnex Constantia Flexibles Germany Gmbh Draka Polymer Films BV Thyssenkrupp Rasselstein Klaus Dahleke KG IMCD Eastman Chemical Clariant Plastics & Coatings AG		

3.3.10 Conclusions

Currently, the aromatics industry in Europe employs directly an estimated 20.0000 employees and indirectly creates over 1 million jobs in the wider industry value chain, being a part of a much bigger refinery-based employment (Vito 2013). An expected 30% replacement of aromatics by the bio-aromatics market (Star-Colibri 2011) may produce 300,000 new green jobs along the bio-aromatics value chain.

At the innovation front; new bio-aromatics will create new materials with relevance for the innovation in EU-economy. Thus, EU will gain or maintain leadership position in novel high-end markets.

3.4 Perspective study 3 – Products and applications based on lignocellulosic feedstock from wood

3.4.1 Introduction

The study begins with the discussion of the lumber industry and wood as starting material, laying out important figures and market trends of the production chain. It also reports important figures and market trends on feedstock cost including sawlog, pulpwood and fibers for pellets. Wood products are classified according to several groups starting by quality products involving minimum processing. It reports market and economic facts for the softwood, the hardwood, the fibreboard and particle board and the paper, paperboard and wood pulp markets. It continues with an assessment of the use of wood as energy and energy carrier. The study emphasizes on the production and economics of chemicals from wood with respect to feedstock availability and cost. The potential products are divided into those resulting from two different wood conversion platforms, namely the thermochemical and the biochemical. The study focuses on products of the second platform, because biochemical processes preserve the chemical complexity of biomass and produce high value chemicals, most of them discussed in the other studies. This study includes further details on product possibilities and markets. A complete wood biorefinery value chain tree and products are presented and analysed with regards to their perspective.

3.4.2 The lumber industry and wood as starting material

Because of nature's special capacity for synthesis, products made from biomass often have attractive product characteristics. Plants are composed by chemicals produced and organized by "nature's laboratory" in chemical structures which are in cases complex to the extent that they cannot be replicated by human's laboratories. Especially for the case of plants and wood in particular, humans have exploited the superior properties of biologically developed products and traditionally, wood-based products have been in use in everyday life from the ancient times either for building, construction and decoration or for energy production for heating, protection, warfare and cooking purposes.

A whole industry has evolved around the production and exploitation of wood. Else called the lumber industry it is an economic sector concerned with forestry, logging, timber trade, and the production of forest products, timber/lumber, primary forest and wood products (e.g. furniture) and secondary products like wood pulp for the pulp and paper industry. Processing and products differs especially with regard to the distinction between softwood and hardwood. Softwood is the source of about 80% of the world's production of timber, (UNITED NATIONS 2017) with traditional centres of production being the Baltic region (including Scandinavia and Russia), North America and China.

The basic argument for the positive environmental impact of wood is that growing trees takes carbon out of the atmosphere storing it first in the forest, which when harvested moves this carbon to storage in products while at the same time displacing fossil intensive products like steel and concrete.

Production chain

The production chain includes logging, which is now typically done using large harvesters and then cutting of the trunks of the felled trees in lumber mills.

BIO-BASED INDUSTRIES Public-Private Partnership | Bio-based Industries Consortium | Horizon 2020 European Union Funding for Research & Innovation

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 745719.

Facts and figures

The total consumption of roundwood – comprising logs for industrial uses and fuel – in the UNECE[6] region was estimated at 1.3 billion m^3 in 2016, an increase of 1.7% over 2015 (UNITED NATIONS 2017). Timber harvests rose in Europe in 2016 for the fifth consecutive year reaching 392 million m^3 in 2016.

Important figures and market trends (source: (UNITED NATIONS 2017)**):**

Softwood is the source of about 80% of the world's production of timber
The total consumption of roundwood – comprising logs for industrial uses and fuel – in the UNECE region was estimated at 1.3 billion m^3 in 2016, an increase of 1.7% over 2015
The timber harvest rose in Europe in 2016 for the fifth consecutive year, to 392 million m^3, comprising 302 m^3 of coniferous species and 90 million m^3 of non-coniferous species.
Industrial roundwood removals have increased by 11.1% in the CIS sub-region7 in the past five years, by 8% in Europe and by 4.2% in North America.
Finland increased consumption most (by 20%) from 2012 to 2016, followed by Portugal (+19.6%), Romania (+12.3%), Poland (+11.6%) and Turkey (+11.1%).

Waste, by products

The global trade of wood chips has increased slowly in the past two years, reaching an estimated 35 million oven-dry metric tonnes in 2016, according to estimates by Wood Resources International. Turkey is the only major chip-importing country not importing wood fibre for the manufacture of wood pulp. Instead, imported wood chips are consumed by the country's large and expanding MDF (medium-density fibreboard) and particle board industry.

Important figures and market trends (source: (UNITED NATIONS 2017)**):**

The global trade of wood chips in 2016 was estimated at 35 million oven-dry tonnes, with the majority being hardwood chips to China and Japan.

Feedstock cost

Sawlog

Although European softwood lumber production and coniferous sawlog demand increased by about 3% in 2016, sawlog prices fell in local currencies and, in many countries, were the lowest they had been for five years. In the first quarter of 2017, the European Sawlog Price Index (ESPI-€) was €83.12 per m3, which was almost 7% lower than in the same quarter of 2015. The ESPI-€ has fallen by 8.3% since the record high in the first quarter of 2014, with the biggest declines occurring in central and northern Europe (Wood Resources International 2017).

[6] The UNECE region covers more than 47 million square kilometres. Its member States include the countries of Europe, but also countries in North America (Canada and United States), Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) and Western Asia (Israel) (see map). The UNECE had a membership of 34 States in 1991; less than four years later membership had risen significantly as a result of the disintegration of the Soviet bloc. Today, UNECE has 56 member States (UNECE 2018).

[7] The Commonwealth of Independent States (CIS), is a political and economic confederation of nine member states and two associate members, all of which are former Soviet Republics located in Eurasia (primarily in Central to North Asia), formed following the dissolution of the Soviet Union. The CIS members are: Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Armenia, Moldova, Russia, Tajikistan and Uzbekistan.

Wood raw-material costs are typically in the range of 60-70% of the total production cost for European lumber producers (UNITED NATIONS 2017).

Pulpwood

The Global Softwood Fiber Price Index, which tracks pulpwood costs on four continents, fell by 3% in 2016; in the first quarter of 2017 it reached its lowest point since the third quarter of 2004 (see Figure 30).

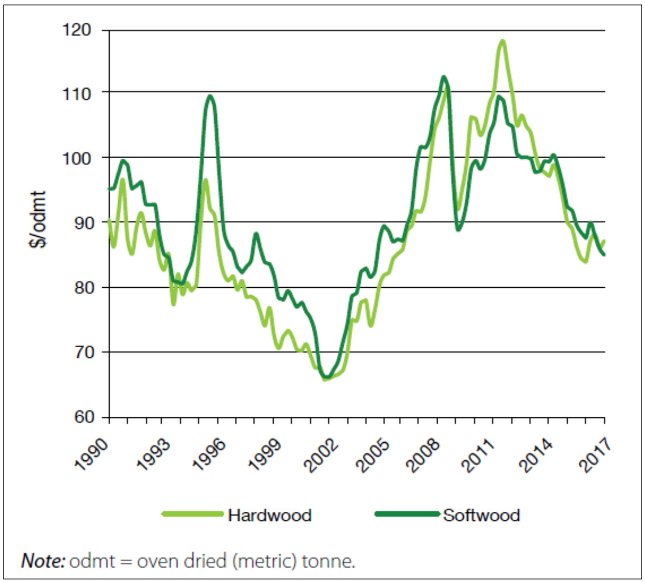


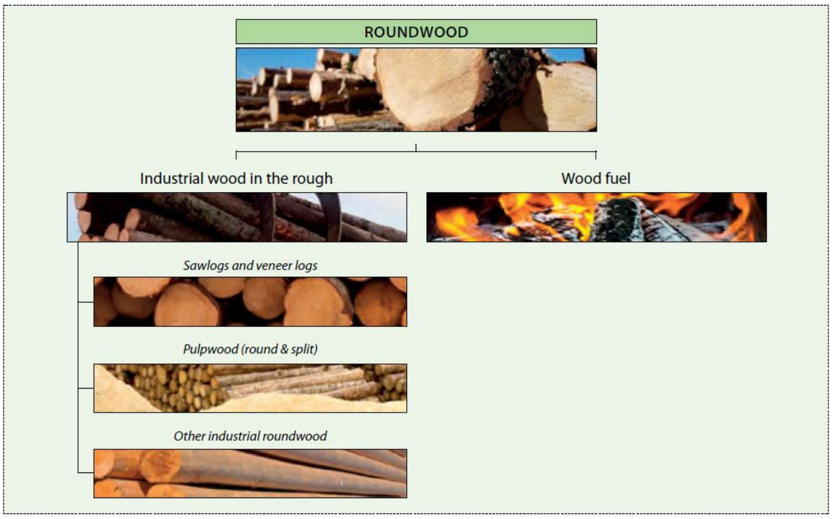
Figure 30 Global wood-fibre price indices for softwood and hardwood, 1990-2017. Source: (Wood Resources International 2017)

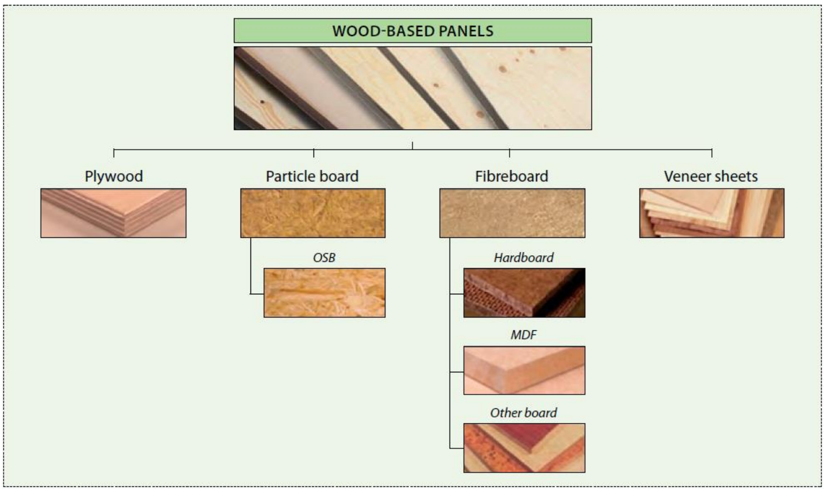
Fibers for pellets

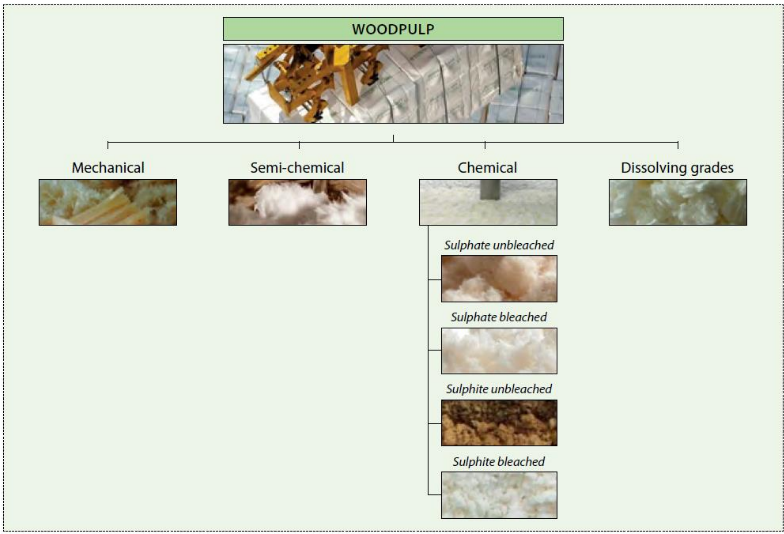
According to (Wood Resources International 2017), the pellet feedstock price indices for North America and Canada have declined 26% and 15% respectively.

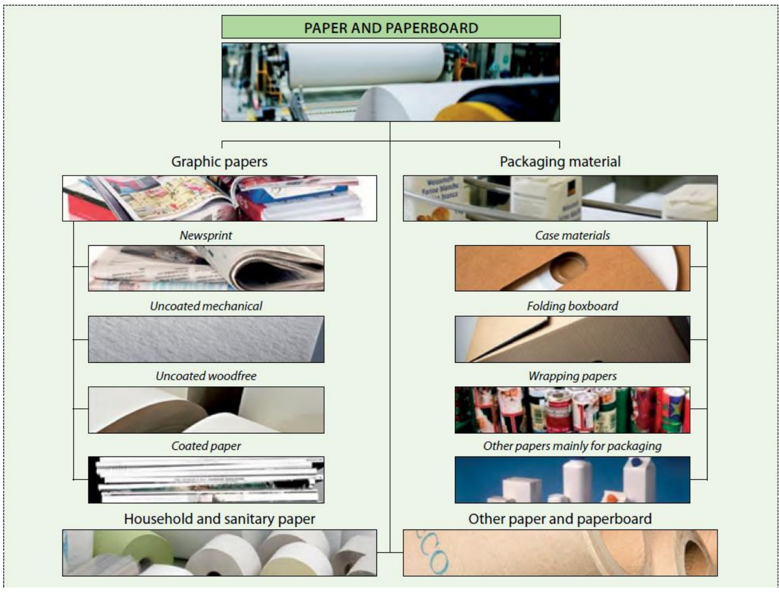
3.4.3 Groups of wood products

The important breakdowns of the major groups of primary forest products are diagrammed below. In addition, many sub-items are further divided into softwood or hardwood. These are: all the roundwood products; sawnwood; veneer sheets; and plywood. Items that do not fit into listed aggregates are not shown. These are wood charcoal; wood chips and particles; wood residues; sawnwood; other pulp; and recovered paper.


ROUNDWOOD
Industrial wood in the rough
Wood fuel
Sawlogs and veneer logs
Pulpwood (round & split)
Other industrial roundwood


WOOD-BASED PANELS
Plywood
Particle board
Fibreboard
Veneer sheets
OSB
Hardboard
MDF
Other board


WOODPULP
Mechanical
Semi-chemical
Chemical
Dissolving grades
Sulphate unbleached
Sulphate bleached
Sulphite unbleached
Sulphite bleached



3.4.4 Quality products involving minimum processing

While softwood primarily goes into the production of wood fuel and pulp and paper, hardwood is used mainly for furniture, floors, etc.. Both types can be of use for building and (residential) construction purposes (e.g. log houses, log cabins, timber framing). Softwood is typically used in construction as structural carcassing timber, as well as finishing timber. Hardwoods are employed in a large range of applications, including fuel, tools, construction, boat building, furniture making, musical instruments, flooring, cooking, barrels, and manufacture of charcoal.

Softwood market and economics

Demand and production increased in all the major sawn softwood markets in 2016, the first year in a decade this has occurred. Apparent sawn softwood consumption rose by 8% in North America in 2016 and by 2.8% in Europe. There was a small gain in consumption (0.9%) in the CIS sub-region. Europe's sawn softwood production increased by 2.9% in 2016, to 107.8 million m^3. Notable gains were in Finland (+0.8 million m^3), Turkey (+0.7 million m^3), Germany (+0.7 million m^3) and Austria (+0.5 million m^3).
European sawn softwood exports increased by 3.8% (to a total volume of 49.5 million m^3) in 2016, compared with only 1% growth in 2015. This increase was remarkable considering that exports decreased by 10% to North Africa and by 7% to the Middle East. European sawn softwood exporters made gains in the key markets of China (+37%), Japan (+15%) and the US (+31%, on small volumes).

Hardwood market and economics

Apparent consumption of sawn hardwood declined by 1.2% in the UNECE region in 2016, to 35.4 million m^3, ending a five-year period of growth. Sawn hardwood production in the UNECE region was flat in 2016, at 41.2 million m^3, falling in Europe and North America but rising in the CIS. Consumption in EU28 countries increased by 1.6% in 2016, to 8.8 million m^3, benefiting from (albeit slow) growth in key sectors of the EU economy, including construction and furniture. European apparent consumption of sawn hardwood increased by 2.0% in 2016, to 12.8 million m^3. Total construction output increased by 2.5% in the EU in 2016 and is forecast to grow by 2-3% annually in the period 2016-2018.

Table 10 Sawn hardwood balance, Europe, 2015-2017 (thousand m^3). Source: (COFFI 2017)

	2015	2016	2017	Change (%) 2015-2016
Production	13,629	13,685	13,689	0.4
Imports	4,771	4,850	4,907	1.7
Exports	5,859	5,743	5,546	-2.0
Apparent consumption	12,541	12,792	13,050	2.0

European sawn hardwood production increased by 0.4% in 2016, to 13.7 million m^3; EU28 production decreased by 0.2%, to 10.1 million m^3. Rises in production in Croatia, France and Germany in 2016 were offset by larger declines in Romania and Slovakia. Total imports of sawn hardwood by European countries increased by 1.7% in 2016, to 4.9 million m^3.

Innovations that aim to

- extend uses into new applications, notably structural applications, through the development of new products made of hardwood cross-laminated timber, glulam and laminated veneer lumber.
- increase the efficiency of wood processing; computed tomography (CT) scans draw on computer-processed combinations of many X-ray images taken from different angles to produce cross-sectional images of the logs so that processing can be customized to optimize yield (Danzer 2016).

Fibreboard and particle board

In total, wood-based panel production increased by 2.8% in Europe in 2016, to 74.7 million m^3 (UNECE/FAO 2017). Apparent consumption of *particle board* decreased by 0.4% in 2016, to 35.9 million m^3. The European Panel Federation[8] The consumption of *fibreboard* in Europe increased by almost 1 million m3 (+5%) in 2016, with European MDF consumption rising by 4.6%, to 15.6 million m^3 (European Panel Federation 2017). Overall plywood consumption in Europe was 8.1 million m^3 in 2016, down by 1.9% compared with 2015 (European Panel Federation 2017).
Figure 31 shows that particle board comprised more than half of total wood-based panel production in Europe in 2016; fibreboard accounted for 30% and OSB for almost 9%. The production of fibreboard increased by 739,000 m3 (+3.2%) in Europe in 2016, to 23.7 million m^3. *MDF* production in European Panel Federation member countries grew by 2% in 2016, to 12 million m^3. Despite four years of growth, Europe's MDF production is still significantly lower than the peak of 21.6 million m^3 in 2007. *OSB* production increased in Europe by 9.6% in 2016, to 6.7 million m^3. European *plywood* production increased by 5.3% in 2016, to just less than 4.9 million m^3.

[8] The European Panel Federation reports information on the following 27 European countries: Austria, Belgium, Bulgaria, Croatia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the UK.

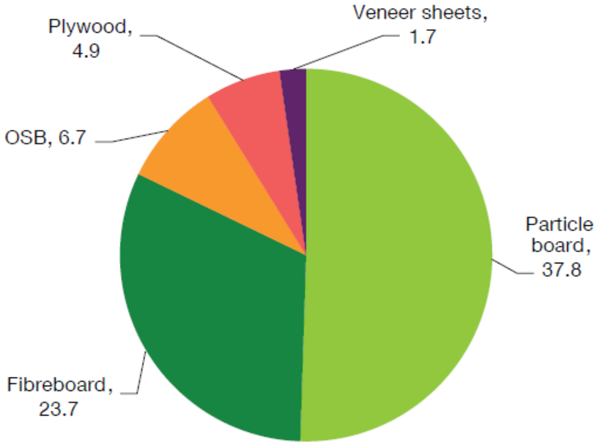


Figure 31 Wood-based panel production, Europe, 2016 (million m³). Source: (UNECE/FAO 2017)

Wood chips are consumed by the MDF (medium-density fibreboard) and particle board industry.

Paper, paperboard and woodpulp

The European pulp industry increased its consumption of wood fibre in 2016 to the highest level in five years. It consumed just over 147 million m^3 of logs and chips in 2016, which was almost 3 million m^3 more than in 2015. CEPI[9] member countries' paper and board production has increased by 1.5% in 2017 compared to the previous year, according to preliminary figures. Total production in 2017 was around 92.3 million tonnes. New capacities and upgrade of existing ones have more than compensated for closures in 2017, similar to 2016. World paper and board production has also increased by 1.5% in 2017, almost reaching 420 million tonnes according to very first estimates. Japan has registered a moderate growth while the US was stable. Production in Canada, South Korea and India contracted. China has grown at a higher speed than the previous year: +4.7% in 2017 against +2.9% in 2016. Brazil and Russia also recorded strong growth (CEPI 2017).

	2015	2016	2017f	Change (%) 2015-2016
Production	98,085	98,200	98,717	0.1
Imports	55,859	56,239	56,311	0.7
Exports	64,780	64,161	64,694	-1.0
Apparent consumption	89,165	90,277	90,334	1.2

Figure 32 Paper and paperboard balance, Europe, 2015-2017 (thousand tonnes). Source: (UNECE/FAO 2017)

Woodpulp production in Europe increased by 2.6% in 2016, to 38.8 million tonnes and the apparent consumption was 1.0% higher, at 44.8 million tonnes.

The use of paper for recycling (recovered paper) in member countries of CEPI rose by 0.1% in 2016, to 47.8 million tonnes. Paper for recycling comprised 46.2% of the fibre used for papermaking in CEPI countries in 2016. Woodpulp accounted for another 39.7%, and the remainder (14.1%) comprised nonwoodpulp and non-fibrous materials (CEPI 2017).

[9] Through its 18 member countries (17 EU members plus Norway), CEPI represents 495 pulp, paper and paperboard companies in Europe.

Important figures and market trends (source: (UNITED NATIONS 2017)**):**

Consumption in EU28 countries increased by 1.6% in 2016, to 8.8 million ma, benefiting from (albeit slow) growth in key sectors of the EU economy, including construction and furniture.

3.4.4.1 Energy and energy carriers

Wood energy markets in Europe are dynamic; they are significantly affected by public policy, weather and changes in production capacity, particularly wood pellets.

Important figures and market trends (source: (UNITED NATIONS 2017)**):**

Woodfuel[10] consumption in the UNECE region increased by 1.0 million m^3 in 2016, to 204.1 million m^3.
Europe accounted for almost 57% of total woodfuel consumption in the UNECE in 2016, i.e. 116.3 million m^3.

A dramatic surge in chip imports by Sweden in 2016 was the result of the start-up, in Stockholm, of one of the world's largest biomass-fuelled combined-heat-and-power plants. The plant is supplied with large volumes of energy chips delivered by ship and train, domestically and from abroad. Monthly chip shipments to Sweden have almost doubled in the last two years, from about 70,000 tonnes per month in early 2015 to 150,000 tonnes per month in early 2017.

The most recent available data show that the primary production of "solid biofuels (excluding charcoal)" in the EU28. grew by 6% in 2015 compared with 2014, to 3,829 petajoules (PJ) (EUROSTAT 2017). This is a higher growth rate than that for overall primary energy production from renewables, which increased by 4.3% in 2015, year-on-year, and which increased by 36% in the EU28 from 2005 to 2015 (see Table 11). Solid biofuels accounted for 44.6% of primary energy production from renewable sources in 2015, constituting the largest source of renewable energy in the EU28, followed by hydro (14.3%) and wind (12.7%). EU28 imports of solid biofuels have increased three-fold since 2005 (EUROSTAT 2017). The consumption of solid biofuels (excluding charcoal) in the EU28 in 2015 was 1,761 PJ by the residential sector, 495 PJ by the paper, pulp and print sector, and 195 PJ by the wood and wood products sector (EUROSTAT 2017).

[10] Wood fuel (or fuelwood) is a fuel, such as firewood, charcoal, chips, sheets, pellets, and sawdust. The particular form used depends upon factors such as source, quantity, quality and application. In many areas, wood is the most easily available form of fuel, requiring no tools in the case of picking up dead wood, or few tools, although as in any industry, specialized tools, such as skidders and hydraulic wood splitters, have been developed to mechanize production.

Figure 33 EU28 total primary energy production from solid biofuels, and share of imports, 2005-2015. Source: (EUROSTAT 2017)

Figures and facts

Primary production of solid biofuels (excluding charcoal) grew by 6% in the EU28 in 2015, to 3,829 PJ.
Europe consumed 20.9 million tonnes of wood pellets in 2015 and 22.3 million tonnes in 2016 (see Table 11).
European imports of wood pellets increased by 4.4% in 2016, to 14.4 million tonnes.

Table 11 Wood pellet production and trade, Europe, 2015-2016 (thousand tonnes)

	2015	*2016*	*Change (%) 2015-2016*
Production	14,620	14,982	2.5
Imports	13,742	14,352	4.4
Exports	7,454	7,046	-5.5

About 42% of pellets consumed in Europe in 2016 were used for residential heating, 36% for power production, 16% for commercial heating and 6% in combined-heat-and-power (CHP) systems.
The consumption of wood chips for wood energy also grew strongly in 2016, to 642,000 tonnes.
Firewood consumption is met from domestic sources. Wood briquettes maintained their market share, at 1.1% of total wood energy consumption.
Syngas for Synthetic Natural Gas (SNG), diesel, or other biofuels e.g. methane, methanol, and dimethyl ether via catalytic processes (Yuping et al. 2015), and the production of bulk chemicals (e.g. ammonia)
o Other energy carriers (biogas, pellets)

Policies - strategies - incentives

The Dutch "stimulation of sustainable energy production incentive scheme" (SDE+) – an incentive scheme for the production of renewable energy in the Netherlands – might spur a new market for

industrial wood pellets in the EU28. However, it is expected that SDE + will disappear in the near future, because there is a lot of opposition against burning biomass feedstock.
The proposal for a revised Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources (RED II) could affect the eligibility of biomass sourcing and the establishment of risk assessments, with uncertain consequences for established interregional supply chains.
Homogenization of value-added tax rates across wood energy sources might increase the price competitiveness of wood pellets.
National carbon pricing policies, could drive greater domestic use of renewable energies, including wood energy.

3.4.5 Chemicals from wood - Feedstock

Regarding the composition of wood it is comprised by mainly cellulose: 41-43%, hemicellulose: 20 – 30% (softwood/conifers), lignin: 27 – 23% (softwood/conifers). There are two main types of wood used by the industry. For the production of chemical and biofuels the wood is converted to and used in the form of wood chips and sawdust. The volume of wood consumed by the pulp industry reaches 150 million m3/y which translates into 90 million t/y assuming average wood density: 640 kg/m^3. The average pulp yield is 45%, thus, the wood pulp production in Europe reaches ~40 million tonnes/y. This leaves 50 million t/y of lignin and hemicelluloses (50-50% w/w) mixture that is so far used for energy production purposes and can be diverted to the production of chemicals.

Feedstock availability and cost

Table 12 reports the production of wood and wood products, pulp, paper and paper products in EU27 (Eurostat 2015), with north and central Europe having the largest production (Figure 34).

Table 12 Wood production in EU27

	Roundwood production		
	Total	Fuelwood	Industrial roundwood
	(1 000 m^3 under bark)		
EU-28	*446 819*	*97 745*	*349 074*
Belgium	:	:	:
Bulgaria	6 372	2 848	3 524
Czech Republic	16 163	2 336	13 827
Denmark (¹)	3 180	1 950	1 230
Germany	55 613	10 494	45 119
Estonia	7 736	2 179	5 558
Ireland	2 908	203	2 705
Greece (¹)	1 217	894	323
Spain	16 719	3 709	13 010
France	51 005	25 962	25 043
Croatia	5 178	1 769	3 410
Italy	5 052	3 004	2 048
Cyprus	11	7	3
Latvia	12 294	1 200	11 094
Lithuania	6 414	2 110	4 304
Luxembourg	381	70	311
Hungary	:	:	:
Malta (¹)	0	0	0
Netherlands	1 173	357	816
Austria	17 550	4 979	12 570
Poland	41 375	5 152	36 223
Portugal	11 533	600	10 933
Romania	*15 315*	*5 079*	*10 235*
Slovenia	5 054	1 242	3 812
Slovakia	8 995	560	8 435
Finland	59 411	7 964	51 446
Sweden	74 300	7 000	67 300
United Kingdom	10 550	1 921	8 629
Liechtenstein	8	4	4
Norway	11 876	1 718	10 159
Switzerland	4 357	1 584	2 772
Montenegro (¹)	915	707	208
FYR of Macedonia (¹)	691	577	114
Turkey (¹)	22 835	4 300	18 535

(¹) 2014 data used instead of 2015

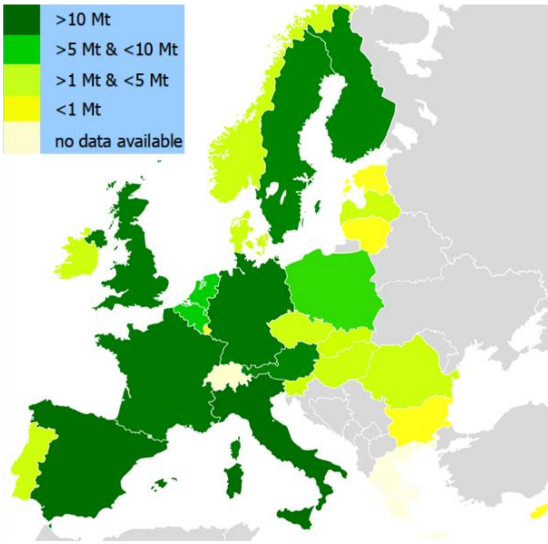


Figure 34 Distribution of the volume of wood production in EU27

According to the European Sawlog Price Index the price of sawlog for the first quarter of 2017 was €83.12 per m^3, and assuming average wood density of 640 kg/m^3, this corresponds to 53.2 €/t. It is low-cost feedstock ~50-60 € / ton d.w., or energy-wise 3-4 € /GJ.

3.4.6 Wood conversion platforms

Two generic wood conversion platforms are used for the production of biofuels and bioproducts; the thermochemical and the biochemical platform (see Figure 35 a and bs).

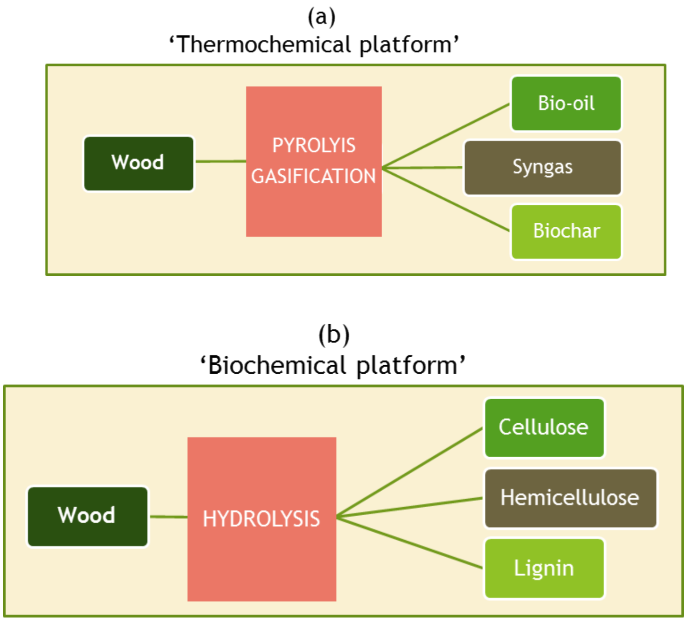


Figure 35 Wood conversion platforms

The thermochemical platform is more versatile with respect to composition of raw material. However, syngas processing chemistry is less developed, and markets are not well developed for bio-oil and biochar.

The most important disadvantage of the thermochemical conversion processes is the loss of valuable molecules with complex structure, which are potential precursors of high value chemicals.
The biochemical platform may receive as feedstock softwood as well as hardwood forestry and pulp mill waste. Wood as feedstock is relatively expensive with prices expected to rise and high value as building material. Typical technologies implemented by the biochemical platform are mechanical pre-treatment for size reduction, hydrolysis using organic or inorganic acid or alkali, or steam explosion. The basic products produced are cellulose, hemicelluloses, lignin or pulp and liquor, which consists of lignin and hemicellulose. The forest biorefinery is an option with significant potential and advantage against grassroot plants, because it builds on existing pulp mills having the established upstream supply chain of the forest industry and more importantly stable feedstock availability. It is able to produce fuels, chemicals, and power streams, while it continues to meet the growing demand for traditional pulp and paper products, thus increasing revenue and at the same time protecting core business. Pulp production is the core business, and black for kraft or brown for sulfite process liquor. The main disadvantages are that hemicellulose and lignin are denatured excluding their higher valuable utilization as pure compounds. Some new processes are developed to overcome these issues, such as the organosolv pulping processes, examples (CIMV acetic/formic acids).

3.4.7 Wood biorefinery value chains and products

Table 13 and Table 14 report the main and most promising wood biorefinery products respectively (Bozell 2008).

Table 13 Basic wood biorefinery products from pre-treatment

Product	Composition of wood
Cellulose	41-43%
Hemicellulose	20 – 30%
Lignin	27 – 23%

Table 14 Carbohydrates and lignin most market qualified products

Products from Carbohydrates	Products from Lignin
Succinic, fumaric, and malic acids	Thermochemical products (gasification, pyrolysis, combustion)
2.5-Furandicarboxylic acid	Macromolecules (carbon fibers, polymer modifiers, resins, adhesives)
3-Hydroxypropionic acid	BTX
Aspartic acid	Pheno
Glucaric acid Substituted coniferols (propylphenol,	Substituted coniferols (propylphenol, eugenol, aryl ethers, etc.)
Glutamic acid	Oxidized lignin monomers (vanillin, syringaldehyde)
Itaconic acid	Diacids from chemical transformations
Levulinic acid	Diacids from biochemical transformations
3-Hydroxybutyrolactone	Aromatic polyols (cresols, catechols)
Glycerol	Cyclohexane and substituted cyclohexanes
Sorbitol	Quinones
Xylitol/arabinitol	

Most of the products included in the lists of Table 14 are examined in this study. Figure 37 presents in the form of value chain tree paths the routes from the main feedstock to these products.

C6 sugars products – Polylactic acid

In this study C6 sugars products are evaluated first. First polylactic acid (PLA) is a biodegradable and bioactive thermoplastic aliphatic polyester and can be synthesized by direct polycondensation of lactic acid or ring-opening polymerization of lactide (LA). In turn, lactic acid is produced predominantly (70–90%) by bacterial fermentation of carbohydrates and the starting material for lactic acid may be any carbohydrate source containing C5/C6 sugars. Wood is a good candidate containing 61% C6 and 73% C5 sugars produced from cellulose and hemicellulose respectively. PLA has various environmental biomedical (sutures and prostheses), and pharmaceutical (matrices for drug delivery systems) applications. More importantly PLA can be used as an alternative to petro-based polymers for packaging, fillers, 3d printing, injection moulding, film and sheet casting, and spinning applications.

The crucial issues for the use of PLA-based materials as alternatives to petro-based polymeric materials include the reduction of the production cost, the enhancement of the mechanical performance and the resistance to hydrolytic/thermal degradation.

Greatly modified PLA-based materials are futile due to the high intrinsic performance of fossil based polymeric materials. For medical and environmental applications, PLA should be used more frequently when the functionality of hydrolysability is required.

C6 sugars products – Sorbitol

Sorbitol is produced by reduction (hydrogenation) of glucose at a high yield; 99.7 %, with few if any technical barriers. It has applications as sweetener and laxative, it also has medical and health care, food and cosmetic uses. Through transformation pathways it leads to derivatives such as isosorbide, anhydro-sugars (PET like polymers for bottles, in use for hot-fill) and propylene glycol (antifreeze, PEF feedstock).

C6 sugars products – Furandicarboxylic acid (FDCA)

FDCA is produced via chemical – oxidative dehydration of C6 sugars. The right selection of dehydrations without side reactions is a technical barrier for its production. To overcome this problem new heterogeneous catalyst systems (solid acid catalyst) have been developed to replace liquid catalysts. Another barrier is the tolerance to inhibitory components of biomass processing streams. The production of PET analogs is one of the direct uses of FDCA as a building block. Potentially new properties for bioplastics (bottles, films, containers) can be attained with the use of FDCA. Starting material for important products with numerous applications (Figure 36).

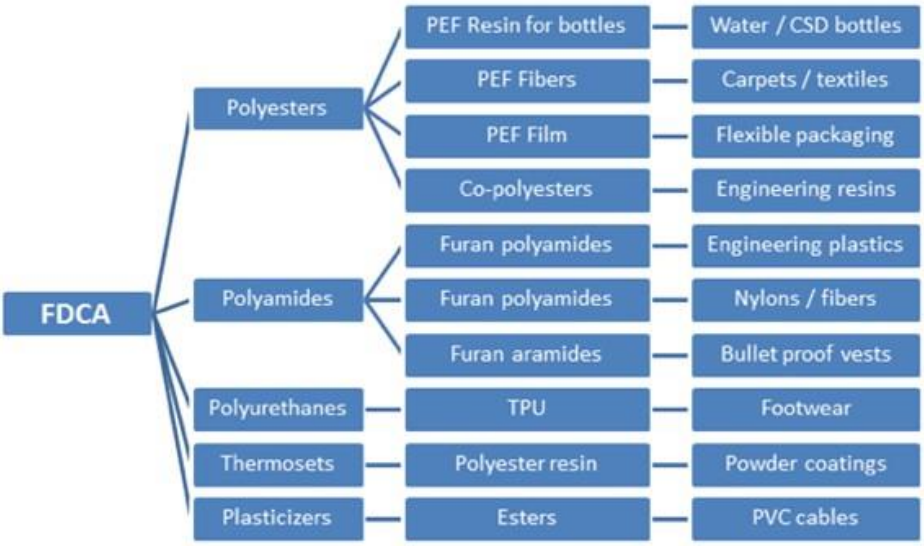


Figure 36 FDCA products and applications

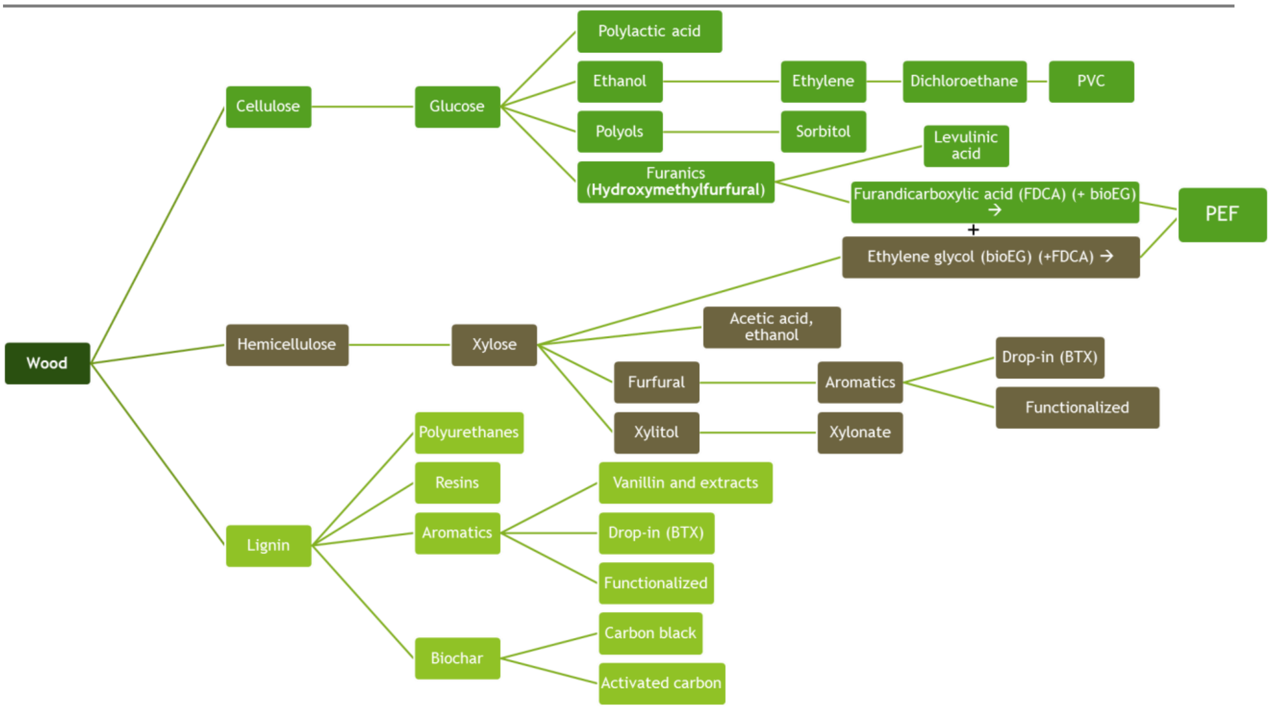


Figure 37 Value chains under study

C6 sugars products – Polyethylene 2,5-furandicarboxylate (PEF)

FDCA can replace PTA to obtain PEF in large applications such as bottles and carpets. The main raw material for PTA is para-xylene (PX) which is generated by oil refining. When also using renewable EG, a 100% renewable PEF can be produced. EG is also produced from bioethanol, or from xylose. The market for virgin PET is currently around 50 million tons per year. PEF has a better performance than PET as it has a higher thermal stability combined with a lower processing temperature. PEF is also seen as a superior material for bottles due to its increased gas barrier properties. PEF finds new applications where PET properties do not suffice, like in smaller serving sizes and light-weighting and also for replacing other packaging materials like glass and aluminium cans.

C6 sugars products – Levulinic acid

It is produced chemically in one step, by acid catalyzed dehydration and decomposition of cellulosics and sugars (also from Hemicelluloses with an additional step) . The process has a high yield and it is starting chemical for numerous other chemicals (Figure 38).

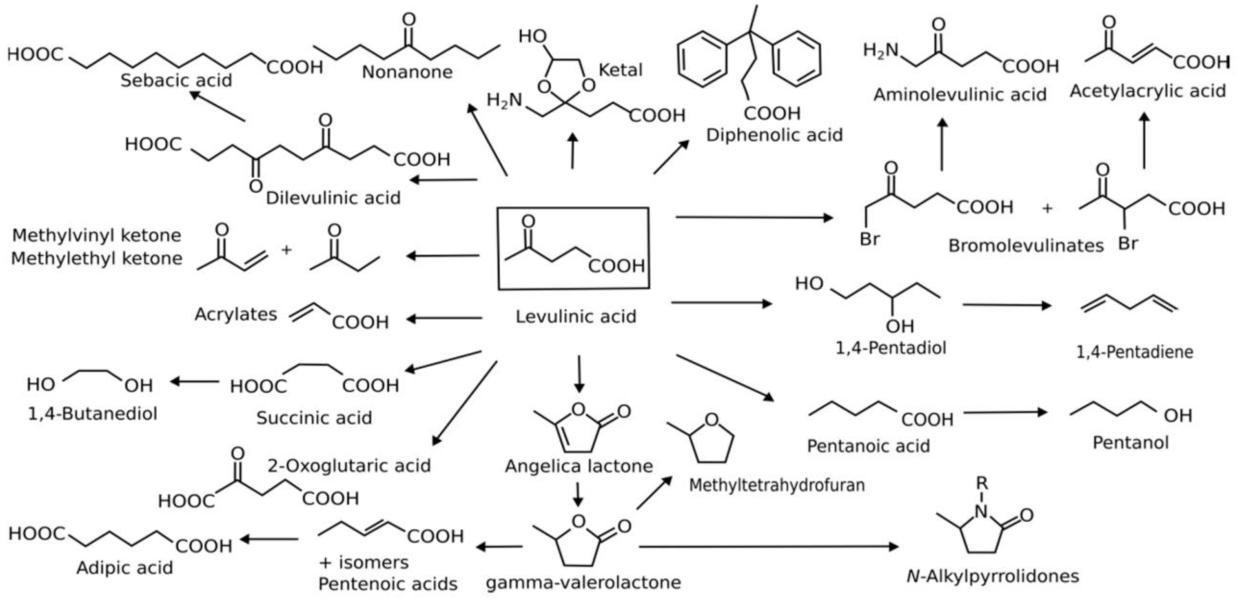


Figure 38 Levulinic acid products

C6 sugars products – Ethylene glycol (EG)

The uses of EG include the production of polymers as building block and intermediate, also as antifreeze and precursor of polyethylene terephthalate (PET). It is produced through liquefaction and enzymatic cleavage of hemicelluloses. 20 million tons are produced annually in the petrochemical industry from ethylene and ethylene oxide. Most important application is the production of PEF.

C5 sugars products – Furfural and aromatics

Furfural is produced through dehydration of xylose. The procedure involves cook up wood under pressure and relatively high temperatures to produces a highly pure lignin that can exceed the value of the ethanol and the hemicellulose fraction, the polymer degrades into the xylose sugars, which under those same process conditions, turns into furfural.

Global Furfural Market Is Expected To Grow At 11.0% Compound Annual Growth Rate (CAGR), by Revenue, and 10.7% CAGR, by volume, from 2017 – 2025

In terms of volume, furfural market size was 464.5 Kilotonne in 2016 and expected to reach 1184.8 Kilotonne by 2025.

Furfural is used as intermediate for the production of furfuryl alcohol for production of furan resin prepolymers exploited in thermoset polymer matrix composites, cements, adhesives, casting resins and coatings. It is also used as intermediate for the production of Tetrahydrofurfuryl alcohol (THFA), which is used as a solvent in agricultural applications. Finally, it is used as intermediate for the production of furoic acid and furan, which is a versatile aromatic with multiple products.

C5 sugars products – Xylitol and Xylonate

Xylitol is produced chemically via hydrogenation of sugars or extraction from biomass pretreatment processes. This is a commercial process. It is also produced biochemically (biotransformation) as the result of pretreatment stream for lignocellulosic processing. Separation from other sugars is the main technical barrier.

The global market for xylitol is estimated at 190.9 thousand metric tons, valued at US$725.9 million in 2016 and expected to reach 266.5 thousand metric tons valued at just above US$1 billion by 2022, by growing at robust CAGRs of around 5.7% in terms of both volume and value. Various products can be produced from xylitol (Figure 39).

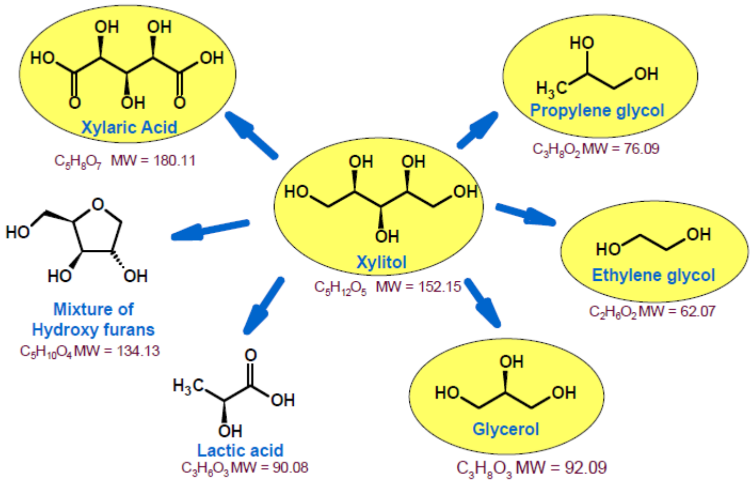


Figure 39 Products from xylitol

Lignin products

There are three lignin product categories:

- power,fuel and syngas
- macromolecules
- aromatics and miscellaneous monomers

The categories themselves fit into near-, medium- and long-term opportunities:

- Near-term: power, fuel and syngas
- Medium-term: macromolecules
- Long-term: aromatics and miscellaneous monomers

Lignin products – as macromolecules

Nearly three-quarters of commercial lignin products are believed to lie within at dispersants, emulsifiers, binders, and sequestrants applications. Resins and adhesives offer a large opportunity, especially for formaldehyde-free applications. Formaldehyde is currently considered a carcinogen and its banishment from consumer and packaging goods and building products is highly likely in the near term. Carbon fibre is another possibility for the valorisation of lignin.

Lignin products – Aromatics

Lignin for aromatics has been discussed thoroughly in the aromatics study as the only renewable source of important and high-volume aromatics class of compounds.

3.4.8 Value chain stakeholders

Stakeholders include partners from the BIOPEN project and the BioBased Delta (Biobased Delta 2018):

Concrete and mortar plasticizers **- LigniOx** (LigniOx 2018)
Sugars, lignin, furans, akylphenols, mono-, di- & tri-acids, functionalized phenols - **BIO-HArT** (BIO-HArT 2018)
Furans and aromatics - **Waste2Aromatics** (Waste2Aromatics 2018)
Benzene, styrene, and terephthalic acid - **Arboref** (Arboref 2018)
Furfural and 5-hydroxymethylfurfuran (5-HMF), dienes and dienophiles (maleic acid anhydride and acrylic acid ester) - **SCeLiO-4B** (SCeLiO-4B 2018)
Bio-aromatics for dispersion agents and emulsifiers, resins for ink, foundry, refractory and wood modification, wood adhesives, UV-stabilizers and flavours - **MAIA** (MAIA 2018)
Lignin for polyol replacement in PU resins and PF type resins for gluing and laminate impregnation, and epoxy resins - **SmartLi** (SmartLi 2018)
Bio-aromatics - Project partners of "**From lignin (bio)chemicals"** (Biorizon-projects 2018).

3.4.9 Conclusions

The chemical complexity of lignocellulosic biomass and wood in articular can be preserved and transformed into high value-added chemicals. To this end the biochemical wood conversion platform is preferred to the thermochemical conversion approach. Key products with a significant market potential and quality are the HMF as a precursor of FDCA and PEF. Also, PLA is as recognized in all previous studies also a winning product along with xylitol and sorbitol, which have an origin of biomass also. The availability of wood for bioproducts is a significant issue that must be resolved because many conventional products compete against bioproducts for the use of this type of biomass. The economics of wood bioproducts are satisfactory and point to a good future.

3.5 Perspective study 5 – Algae and seaweed-based products

This section reports on the results of the perspective study on the potential of algae for the production of biofuels and bio-products.

3.5.1 Introduction

When discussing algae, we consider the distinction between macroalgae and microalgae. Macroalgae are basically seaweeds and microalgae are microscopic organisms that, when supplied with the necessary nutrients, form rapidly growing populations and make up the world's phytoplankton in water. There are more than 8,000 microalgae species which are divided into four types: cynaobacteria (blue-green algae), rhodophytes (red algae), chlorophytes (green algae), and chromophytes (all other algae). Each of these types contains hundreds of species. Each species may be thousands of genetically distinct strains. Only a small fraction of these varieties has been studied for possible beneficial use, and there is much ignorance and uncertainty regarding the behaviour and properties of most micro-algae species. Thanks to their enormous biodiversity across thousands of different species, microalgae produce many bioactive compounds with potential use for medical, human health, aquafeed and energy purposes. However, of tens of thousands of different species globally, only a handful have been grown commercially.

Key conclusion:

Research on the behaviour and properties of unexplored micro-algae species must be reinforced

Commonly used algae for bioproducts comprise seaweed, kelp, chlorella, and spirulina. Due to high nutrient excellence, algae products have a potential application in food and feed supplements, nutraceuticals, pharmaceuticals, and pollution control.

Fossil fuel covers the majority of our energetic and chemical needs. However, fossil fuels are limited, and the petrochemical industry has a negative impact on the environment. Conventional biomass feedstocks remain controversial due to the limited land availability and competition with food and feed production. Bioeconomy outputs will ultimately be constrained by land availability.

The idea of using algae for making consumer products is not a new one. Algae are large and diverse group of organisms, typically autotrophic organisms that produce complex compounds such as lipids, carbohydrates, and proteins, using simple substances located in their surroundings. Due to their high protein contents and healthy pigment contents, algae are widely used today as a health food supplement. Microalgae in particular, represent a promising alternative renewable source since they can be cultivated on non-arable land. Furthermore, microalgae remove and recycle nutrients from wastewater and flue-gases, thus providing additional environmental benefits. Investigating the production of non-fuel products could play a major role in turning economic and energy balances more favourable. Microalgae offer interesting applications in the nutrition field being high in antioxidants, pigments, polyunsaturated fatty acids and proteins.

Key observation:

Algae on the other side offer the potential of efficient carbon capture and conversion of solar energy to bio-based products including transport fuel largely **disconnected from land issues**.

For the conversion of CO_2 from the atmosphere or captured in industrial processes into high added-value products and biofuels algae represent a promising alternative. However, macro and micro-algae remain largely untapped sources for the production of biofuels and bioproducts for nutritional, aquaculture, medical and environmental applications.

3.5.2 The market and market trends for algae and algae prodcuts

The world production of macroalgae for commerce amounts to $5.5–6 billion per year (McHugh 2003; Pulz and Gross 2004). While the food industry is estimated to generate $5 billion per year, a further $600 million is estimated to have been generated from hydrocolloids extracted from the cell wall of the macro-algae at an average value of about $10,900 /ton. Sales of one of the dried kelp, called Nori, are estimated to be $1 billion–a high value product worth $16,000 / ton. Overall, the global algae products market is projected to grow at a CAGR of 5.3% over the forecast period (Market Research Future 2017), and the global seaweed market is expected to grow at a CAGR of 10.28% during the period 2017-2021 (Grand View Research 2018).

The global agar market size was estimated at USD 255.18 million in 2018 and is anticipated to grow at a CAGR of 5.1% from 2018 to 2023 (Mordor Intelligence 2018). The exponential growth in the usage of this product is attributed to its functional and health benefits. It contains 80% of fibers and can be used as an appetite suppressant. It is also an important culinary ingredient as it acts as a substitute for gelatin and can be used as a thickener soups, in fruits preserves, ice cream and other desserts.

Carrageenan market value was estimated to be $720.3 million in the year 2013, it is growing at 5.3% annually and is projected to reach $931.6 million by the end of 2018. Carrageenan accounts 13.3% share of the global food & beverage hydrocolloids market. The market is poised to grow its market share to 13.4% by the end of 2018. Substitutes of carrageenan are gelatin, pectin, and guar and xanthan gum comprising 21.5%, 17.7%, 9.9% and 8.0% respectively, of the global food & beverage hydrocolloids market (Micro Market Monitor 2017).

According to a recent report (Persistence Market Research 2018), the global microalgae market is set to record an average expansion between the forecast period 2017 -2026. Over US$ 75 Mn revenues are estimated to be procured from sales of microalgae across the globe.

Key conclusion:

The trend towards addressing higher value markets such as condiments for human food, and inclusion in cosmetics products should be encouraged.

The trend towards addressing higher value markets such as condiments for human food, and inclusion in cosmetics products should be encouraged, in order to develop this feedstock for further high value applications (such as novel uses for hydrocolloids in drug delivery, personal care and food, fucoidins for functional foods), especially in the context of industrial biotechnology and biorefining. In addition, companies and research institutions are preparing for scale-up of production on long lines, to underpin the longer-term development of this feedstock for commodity chemicals and bioenergy (Figure 40).

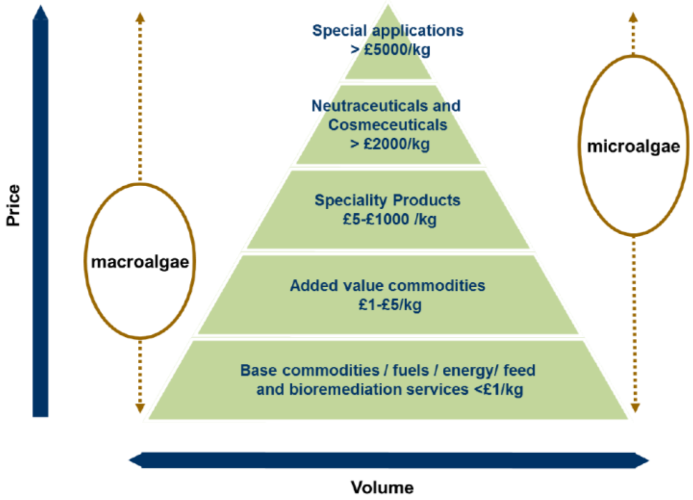


Figure 40 Current capacity and pricing of products from micro- and macroalgae

3.5.2.1 Market segmentation and regional analysis

Algae products are segmented on the basis of the source, which includes macro-algae, micro-algae, and others. The macro-algae segment is dominating the market. The macro-algae are cheap and involve less cost in growing. Furthermore, extraction of phyto-ingredients from macro-algae is relatively simpler than from micro-algae. However, micro-algae products are used in the nutraceuticals industry for the production of products such as supplements and energy drinks, which is expected to grow rapidly during the forecasted period. On the basis of product application, the algae products market is segmented in food supplements, feed supplements, nutraceuticals, pharmaceuticals, pollution control, paints and colorants and others. The nutraceuticals are dominating the market because of rising health awareness. However, the demand for food supplements is expected to experience a high growth owing to health benefits associated with the consumption of algae products.

The global algae products market is segmented into North America, Europe, Asia Pacific, and rest of the world. Europe is dominating the in the algae products market followed by North America. Europe has been accounted for a higher consumption of algae products supplements and food products owing to increasing consumer awareness. Furthermore, high demand for algae in pharmaceutical and nutraceutical industry is considered to be a key driving factor in this region.

Moreover, increasing consumer awareness and high demand for food and feed supplements from countries like India and China, a huge growth is anticipated in the algae products market in Asia Pacific region. Additionally, high focus on R&D in algae products for pollution control is observed, which is expected to encourage the growth of the global algae products market.

3.5.3 Value chains and applications of algae products

3.5.3.1 Algae for fuels

As early as the 1950's algae were researched for natural gas production, and after the 1980's fuel crisis, algae were targeted for their oil producing potential. Algae have been seen as an attractive feedstock for biodiesel because of their capacity to produce oil under stresses, frequently using waste products as nutrients (Sheehan et al. 1998). Since the 1980s and 1990s a number of companies have been founded around the concept of using algae for fuels, but over the past 20 years a number of limitations have been realized. The most important of these limitations is the requirement to grow only certain oil producing species or strains. In (Wiley et al. 2011) and (Yanqun et al. 2008) some of the processes that are considered for utilization of algae as a fast growing feedstock for biofuel are presented. Strain selection adds to the cost involved with eliminating wild species contamination risk and limits the means of algae production that are possible. Furthermore, the production of oil often requires the algae to undergo certain stressors to convert to oil production. Stressing the algae both inhibits growth of the algae thereby limiting production potential and complicates the process for oil generation. Finally, oil or other fuels production from algae is targeted at a specific compound in algae and therefore an extra extraction step is required to get the targeted compound. While this process is advantageous compared to traditional crude oil production, it is very costly and limiting in its scope.

Despite many years of effort and a wide range of initiatives e.g. the Aquatic Species Program 1980-1994 ($50m); The Japanese RITE programme of the 1990s (>$250m); EU programmes (>€100m on 86 projects since 1998), only very few companies are cultivating microalgae on a commercial scale and none has large-scale units for biomass production for biofuels and carbon mitigation. This is because fuel-only algal systems are still not economically feasible and additional revenues are required. Yields of microalgal biomass (20-50 t ha-1y-1 in photobioreactors (PBR)s; 10 – 30 t ha-1 y-1 in commercial raceways) for commercial-scale biofuel are too low compared to agricultural crops (49 t ha-1y-1 for maize, 41 t ha-1y-1 for rice, 28 t ha-1y-1 for wheat and 71 t ha-1y-1 for sugar cane). Therefore, the need to maximise land productivity through waste reduction and efficient integration of biomass processing arises. Costs for producing microalgae for biofuel in raceways or PBRs for biofuel are too high compared to costs for producing agricultural residues for biofuel e.g. straw. For a 50,000 m^2 raceway pond, capital costs of €220,000 and operating costs of >€6000 - €8000 have been estimated, compared to <€7,000 and €20-€30 for the costs of wheat straw respectively (Hochman and Zilberman 2014). These factors limit the scale of energy production and GHG abatement from algae by default to the amount of algal biomass that can be produced to support profitable applications. Similar arguments related to productivity, capital costs, technical constraints, and uncertainty are made in (Gallagher 2011) and underline the constraints on the economic viability of algae as biofuel. Although new cost reducing strategies for utilizing algae for fuel production will be identified by future research, there is significant economic potential for algae in other applications, some of which can complement the use of algae as fuels resource also.

Major limitations of commercialization of algae biofuels include (1) algae mass culture oil content; (2) harvesting methods; (3) separation techniques; and (4) supply of CO2 and other nutrients (Miao et al. 2004; Lundquist et al. 2010).

Biorefineries which integrate biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass, offer a solution (D-Factory 2017). The challenges are to explore and develop macroalgae and microalgae to identify potential bioproducts, and further cultivate useful microalgae to produce a range of bioproducts in a sustainable and profitable way. Small-scale cultivation and industrial scale production of microalgae has evolved in the last few decades. Several substantial applications have been established. These applications include food, feed, fatty acids, polysaccharides, food colouring, fine chemicals and waste water treatment applications.

3.5.3.2 Food and feed products

Many types of dried seaweed are being used as food products, mainly in salads and for seasonings, with currently species of Rhodophhyta and Phaeophyta used industrially to produce 7.5–8 million tons of wet seaweed annually.

Many microalgae have a high nutritional value. They contain proteins, vitamins and minerals, and non-saturated fats. Moreover, they can yield higher outputs for the same levels of water and land. These characteristics led to the success of the production of Spirulina, a microalga that grows isolated in a monocultural setting (another type of micro-algae grown isolated in a monoculture is Dunaliella salina). It has commercial success as a "health food" and is a component of many health food products. Worldwide, Spirulina is grown in many countries for animal feeds and food nutrition supplement (FAO Fisheries and Aquaculture Secretariat 2010). Other important species include Chlorella, Dunaliella, Nostoc, and Aphanizomenon.

Culture of the freshwater algal Haematococcus pluvialis was developed in a few countries and is used for the extraction of astaxanthin (FAO 2010), a natural antioxidant. Much research is needed to develop large-scale food and feed production from algae—one needed to identify species, production, procedures, etc..

Key conclusion:

> Much research is needed to develop large-scale food and feed production from algae—one needed to identify species, production, procedures, etc.

3.5.3.3 Fatty acids

Certain unsaturated fatty acids in triglycerides have desirable therapeutic and health-promoting properties. Research has shown that omega-3 fatty acids reduce cholesterol and fat levels in the blood and "cleanse" the lining of blood vessels (Simopoulos 1991). The medical use of omega-3 fatty acids for prevention and treatment of heart disease is increasing via prescribing fish oil to heart patients. Usually, this treatment continues throughout the lifetime of the patients. Moreover, some doctors prescribe similar dosages to individuals with high-risk profiles with respect to coronary diseases. As evidence of the effectiveness of this treatment spreads, its adoption is likely to grow.

Studies have shown that omega-3 fatty acids have the effective therapeutic properties dealing with rheumatoid arthritis and immunodeficiency diseases, and doctors are considering prescribing pills derived from fish oils to combat these diseases (Yetir 1988). The product extraction directly from the algae is likely to be superior to the cod liver oil as (1) it will not have the off flavour of cod liver and (2) it will be more "pure" product and thus more effective.

Key conclusion:

The medical discoveries about the therapeutic properties of omega-3 fatty acids suggest a very large market to algal-derived fatty acids. The superiority of the microalgae derivative and the continued growth in demand for omega-3 fatty acids suggest much higher sales potential for fatty acids derived from algae. There is a substantial market for omega-3 fatty acids, and they can be marketed through distributional channels of drugs and health products.

3.5.3.4 Polysaccharides

The economic value of the macroalgae derivatives goes much beyond their usefulness as food products. Polysaccharides that can be produced from algae are chemicals used as viscosifiers (thickening agents), fluctuating agents, and lubricants. The value of polysaccharides varies according to their use, availability, and purity. They include macroalgal derivatives such as carrageenan and agar.

Agar is a mixture of two components: the linear **polysaccharide** agarose, and a heterogeneous mixture of smaller molecules called agaropectin. It forms the supporting structure in the cell walls of certain species of algae and is released on boiling is the most diversely used macroalgae derivative with substantial worldwide sales. Agar is a class of vegetable gums that is derived from the two varieties of seaweed–Gelidium and Gracilaria. It is a very strong gelling agent with unique properties. Agar is not poisonous to humans, has no nutritional content, does not rot, and can absorb liquids and swell. The gel it generates may survive a wide range of temperatures; is indigestible by most bacteria; and is very elastic, resilient, and clear. Agar and its derivatives have a wide variety of uses. The value of agar products varies substantially according to their quality. Carrageenan and alginates are two other macroalgae derivatives much used as gums, emulsifiers, and gels. Annual sales of these products are in the hundreds of millions of dollars.

Key conclusion:

Algae generate also other complex and unique polysaccharides and many algal derivatives are irreplaceable. Microalgae are the source of important and commercially used polysaccharides, and the market for these algal derivatives are in the hundreds of millions of dollars.

Microalgae such a Porphyridium cruentum/Rhodophyta (Fuentes et al. 1999) are commercially used to produce polysaccharides. Under the right conditions, 15–55 % of the weight of the microalgae can be extracted as polysaccharides. Taking a very conservative approach—assuming 15 % polysaccharides share in dry weight, medium yields (5 t of dry weight algae per 1,000 m2), and high cost ($30,000 per 1,000 m2 annual total cost)—the break-even price for polysaccharides production is $40 per kg, which is within the medium range of market value for polysaccharides. Taking a slightly more optimistic view—30 % polysaccharides share in weight, medium yield (5 t per 1,000 m2), and low cost ($20,000 per 1,000 m^2)—the break-even price is less than $15 per kg, quite a modest price for many polysaccharides.

Key conclusion:

Thus, polysaccharides from microalgae have good economic potential.

3.5.3.5 Food Coloring and Osmoregulators

There is a growing demand worldwide for organic food colouring. Regulating agencies constantly limit the range of permissible chemical food colouring, and the regulatory process will be even stricter if and when organic substitutes are available. The volume of the market for food colour is immense—in the billions of dollars annually. Microalgae can be used as a source of many organic food colouring. Some microalgae contain substantial amounts of other types of carotenes in addition to beta-carotene. Other types of colouring appear in microalgae as well. In pure form it can fetch up to $1,000 per kg. It has been argued that the potential of microalgae, as a source of food colouring, is limited because algal-derived food colouring is not photostable. Namely, they tend to bleach with cooking. Nevertheless, in spite of this limitation, the potential market for microalgae-derived food colouring is vast.

Key conclusion:

The potential market for microalgae-derived food colouring is significant.

Osmoregulators are carbohydrates that can affect osmotic processes. Glycerol is the most notable member in this compound category, which included other commercially viable products as well. Substantial weight of the dry weight of several algae, e.g., up to 50 % (Dunaliella salina), can be transformed to osmoregulators under the appropriate conditions. Microalgae compete with bacteria and animal fat as sources of osmoregulators.

Key conclusion:

Research should and is likely to discover valuable osmoregulators that can be produced from microalgae.

3.5.3.6 Algae for bioplastics

In the case of algae for bio-plastics, it is the high protein content found in the biomass that is attractive. The high protein contents in algae (reaching as high as 65% of the dried biomass in some cases) make them naturally capable of behaving like a polymer after exposure to heat and pressure. Since algae naturally tend towards high protein content when nutrients are abundant and only move towards starch or lipid production when nutrient availability is low, strain specificity is not an issue and extraction is not required. With a much simpler means of production the use of algae for plastics is a very economical and sustainable practice.

Additionally, since the waste products of lipid extraction are generally a high protein biomass residue, co-product strategies exist that can be used to produce plastics as a byproduct from fuels production. The diversity of sources available for production makes the biomass targeted approach for algae plastics both very compatible with current industrial algae production, and uniquely compatible with wild harvested or low maintenance algae farming methods.

Key conclusion:

Algae for plastics is a mature, economic and sustainable solution.

3.5.3.7 Perspectives and limitations

Algae products are rich in protein and contain essential amino acids, which help in boosting human metabolic process like enzyme production. Also, high content of Omega-3 and Omega-6 fatty acids in algae products makes is a good source of energy in food and feed. Thus, the demand for algae products is high from the food and feed industry.

Moreover, occurrence of key phyto-ingredients like beta-carotene, carotenoids, omega 3 fatty acids, and astaxanthin in algae products supplementing health benefits is experiencing a high demand from food supplement manufacturers, pharmaceutical, and nutraceuticals industry. Furthermore, high demand for algae products in paints and colorants industry is adding up the growth of algae products market.
Among the key findings in this study is that the demand for algae products is increasing from nutraceuticals industry, the aquaculture segment has massive opportunity and that biofuels made from algae have potential for better alternative to conventional energy provided that they are supplemented economically by the production of other algae bioproducts of high value.
The development of molecular genetics (biotechnology) raised much hope in improving algae strains and making them commercially viable but also brought much fear, because large portions of the population are suspicious and oppose this technology.

3.5.4 The European perspective and initiatives

Natural advantages for algal cultivation, including extensive areas of non-arable land, unrestricted seawater or saline water and plenty of sunshine and warm weather, can be offered by several South European Countries but also North Africa and Easter Mediterranean countries. Europe has recognized the potential of micro algae and has established the Science and Technology Network EUAlgae (European Network for Algal-Bioproducts) financed by the European COST programme (COST 2014). EUALGAE is created to stimulate not only interaction among research groups across Europe but also to foster cooperation between academia and industry. This scientific platform will generate a synergistic approach for utilization of microalgae biomass for sustainable fuels and fine chemical products.

The first step for establishing sustainable value chains for the production and processing of micro algae is to optimize the microalgae growth and definition and manipulation the population dynamics. In order to overcome the main bottlenecks preventing the economic development of large scale photobioreactors the following constraints related to microalgae productivity must be addressed: design of photobioreactors (PBRs) and the definition of the nutrients source (synthetic vs wastewater) and nutrition modes; the harvest of microalgae and the technologies for disrupting cell wall in accordance to targeted bioproducts; the refining of microalgae into its value components which is the main bottleneck of the bio-refinery approach in the downstream processing of micro-algal high-value products such as polyunsaturated fatty esters (PUFAs), antioxidants and pigments; the development of valorisation methods from intermediates and sub-products of microalgal biomass from previous valorisation processes with focus in the optimal valorisation processes to obtain useful products as food and feed ingredients, chemicals, materials, as well as liquid and gaseous energy carriers; the proof of sustainability using economic analysis and Life Cycle Assessment (LCA); and last but not least the industrial scale process design and scale-up.

Key conclusion:

Research on the behaviour and properties of **unexplored** micro-algae species must be reinforced.

3.5.5 Value chain stakeholders

An extensive review of stakeholders has been produced by the EnAlgae project (EnAlgae Project 2019). It reports technology expertise in NW Europe (EnAlgae Public Reports 2014) and more specifically in the regions of France, Belgium, Great Britain, Germany, The Netherlands, Switzerland and Luxembourg, and Ireland. In total 284 institutions working with algae could be identified in North-West Europe. The majority of these stakeholders (60%) are academic stakeholders, which mainly carry out research activities. The other stakeholders are from commercial institutions. It needs to be noted, though, that most commercial algae stakeholders are also carrying out algae research. The separation into the different types was mainly done in order to evaluate the foci of the work of scientific and commercial stakeholders and to which extent they match to each other.

The number of stakeholders in the different countries varies significantly from no algae stakeholders being identified in Luxembourg to over 77 stakeholders identified in the UK. The United Kingdom consequently has the highest representation of stakeholders working with algae in North-West Europe followed by the Netherlands and France. 27% of all identified algae stakeholders in NW-Europe work in the UK and 18% in France and the Netherlands respectively.

Looking at the respective break down into scientific and commercially oriented stakeholders it can be noted that the UK is also the country with the most unequal distribution of these 2 groups. 78% of the identified UK-stakeholders are research institutions. In most of the countries that were included in the survey the ratio differs between these two groups differ not so strongly. Nevertheless, the scientific stakeholders account for the majority in the algae sector. Only in France, the collected data gave a different picture: 64%, hence a significant majority, of the French stakeholders represent commercially driven algae businesses. In Ireland, the ratio of scientific and commercial stakeholders is the most equal one (EnAlgae 2014).

3.5.6 Conclusions

Algal technologies have considerable potential to contribute to economic growth in the EU. To realize this potential for delivering sustainable products and services, and for expanding the knowledge-based bioeconomy, it is essential to **invest into scale-up cultivation facilities** for macro- and microalgae, to **develop the concept of integrated biorefining**, and to **harness EU expertise** for the development of a thriving, globally relevant industrial biotech and knowledge industry.

Factors that influence the potential for success include market pull, technology readiness and existing expertise, international competitive landscape, fit with legislative and regulatory drivers, as well as geographical, financial and environmental competitive advantages. The largest market pull is found for products and services that in the current technoeconomic assessments are most challenging to achieve: **biofuels**, **bulk feed** and **chemicals**, and **large-scale bioremediation**, e.g., for CO2 capture and storage and wastewater treatment.

Short to medium term commercially viable opportunities are high value products from both macro- (condiments and premium sea vegetables, high value uses of hydrocolloids) and microalgae (increased production of established and emerging bioactives, e.g., DHA, EPA, pigments, antioxidants, sunscreens); bioremediation using macro- and microalgae linked to feed and fertiliser production and decentralized energy generation via AD; knowledge industries for technology provision and consulting. And, in the medium to long term, integrated biorefining of micro- and macroalgae coupled to fractionation or thermochemical conversion for a suite of chemical and energy products as well as novel bioactives through bioprospecting (micro- and some extent macroalgae) and metabolic engineering (microalgae) for pharma, cosmetics, nutrition present a significant perspective.

Commercial utilization of algae, beyond biofuels, is economically viable, and there is a worldwide market for algal derivatives that is estimated to be in the billions of US dollars. While application of algae as biofuel has gained much attention, the literature suggests that some algal derivatives, which researchers worked on during the last several decades, matured and proved to be quite lucrative. Others are still at the research and development stage or are just been thought of.

Energy production from algae has gained much attention, but current technologies cannot compete with fossil fuels production. Policy can facilitate the adoption of these technologies of algae technologies as part of a green economy, but such policy emphasis may misfire if the algae sector cannot stand on it’s own feet and compete after a relatively short period of transition and learning.

The most vital enabler, common to both macro- and microalgae and relevant to the whole value chain of products, would hence be the immediate **provision of scale up and demonstration plants** that allow collection of reliable data on yields and financial as well as environmental sustainability. Complemented by mapping of sites across the EU where the biomass could be grown sustainably, this would enable a meaningful projection of the potential scale of production.

4 Life Cycle Analysis for bio-based products

Policymakers worldwide are promoting the use of bio-based products as part of sustainable development. Nonetheless, there are concerns that the bio-based economy may undermine the sustainability of the transition, e.g., from the overexploitation of biomass resources and indirect impacts of land use. Adequate assessment methods with a broad systems perspective are thus required in order to ensure a transition to a sustainable, bio-based economy. A review of the scientifically published life cycle studies of bio-based products in order to investigate the extent to which they include important sustainability indicators is conducted by (Martin et al. 2018). To define which indicators are important, they referred to established frameworks for sustainability assessment, and include an Open Space workshop with academics and industrial experts. The results suggest that there is a discrepancy between the indicators that they found to be important, and the indicators that are frequently included in the studies. This indicates a need for the development and dissemination of improved methods in order to model several important environmental impacts, such as: water depletion, indirect land use change, and impacts on ecosystem quality and biological diversity. The small number of published social life cycle assessments (SLCAs) and life cycle sustainability assessments (LCSAs) indicate that these are still immature tools; as such, there is a need for improved methods and more case studies (Martin et al. 2018).

4.1 Indicatiors

The following sustainability indicators (with units of measurement) and aspects to be important, besides the life cycle cost have been identified by (Martin et al. 2018):

- From the PB framework (Steffen et al. 2015): climate change (temperature, rainfall (mm) – volume/area), stratospheric ozone depletion (Dobson Unit (DU)), chemical pollution (ppm), atmospheric aerosol concentration (ppm), nitrogen and phosphorus emissions (ppm), acidification of oceans (pH), freshwater consumption (tonnes per tonne of product), land-system change (diverted hectares), and biodiversity loss;
- From the PEF guide (European Commission (EC) 2013): climate change, ozone depletion, freshwater eco-toxicity (ppm or mg/L), human toxicity (cancer and non-cancer impacts), emissions of particulate matter (ppm), human health impacts of radiation, photochemical ozone formation, acidification (pH), eutrophication (terrestrial and aquatic) (phosphorus in ug/l (micrograms per liter), or ppb (parts per billion), water depletion (tonnes per tonne of product), depletion of fossil and mineral resources (tonnes per tonne of product), and land transformation (diverted hectares);
- From the UNEP-SETAC guide for SLCA (Benoît and Mazijn 2009):
    - Impacts on workers: freedom of association, child labor, fair salary, working hours,
    - Forced labor, discrimination, health and safety, and social benefits and security;
    - Impacts on local community: access to material and immaterial resources, delocalization and migration, cultural heritage, safe and healthy living conditions, indigenous rights,
    - Community engagement, local employment, and secure living conditions;
    - Impacts on consumers: health and safety, feedback mechanisms, consumer privacy,
    - Transparency, and end-of-life responsibility;
    - Impacts on other value-chain actors: fair competition, social responsibility,
    - Supplier relationships, and intellectual property rights; and
    - Impacts on society overall: public commitments to sustainability issues, contribution to
    - Economic development, the prevention and mitigation of armed conflicts,
    - Technology development, and corruption.
- From the Open Space workshop (Ekvall 2017) (Climate impact, Biodiversity, Working conditions, Water use, Ecosystem functions, Resource use, Emissions of particulates, Odor (odor units per cubic meter of air

[o.u./m^3]), Human health, Corruption/Human rights, Regional value creation, Resource availability, Eutrophication, Intragenerational and intergenerational human well-being): climate change, biodiversity, working conditions, water use, ecosystem functions, and the use of various resources.

5 GAPS AND CHALLENGES

Table 15 classifies the gaps and challenges of the biobased sector in relation to the 5 perspective studies.

Table 15 Classification of gaps and challenges for the biobased sector

Technical	Economic	Social	Political
• Main challenges for the market diffusion of biopolymers for coating and packaging, the humidity and air barrier, thermal stability and mechanical stress properties, which have to be further improved, the avoidance of harmful substances migration, microbial stability over substantial time periods (larger than the product consumption horizon) • The drop-in commodities do not differ greatly from their petrochemical counterparts as they do not provide any extra/new functionalities while being produced at a higher price than traditional petrochemical building blocks. • In non-integrated biorefineries only 25 to 50% of the biomass is valorised into final product due to low process efficiency, with the effect of high waste of currently limited	• Main challenges for the market diffusion of biopolymers for coating and packaging are the higher production cost compared to the fossil-based counterparts • The fluctuation of prices of conventionally fossil-based chemicals raises a concern regarding the possibility of the bio-processes to compete in economic terms, especially when – as in current times – the prices (of phenol for example) are being directly attached to the falling prices of oil and gas. • When algae are used for the production of fuels significant issues of productivity, capital costs, technical constraints, and uncertainty arise (Gallagher 2011) and underline the constraints on the economic viability of algae as biofuel.	• Main challenges for the market diffusion of biopolymers for coating and packaging the public opinion and the environmental conscious consumer attitude • The participation of SMEs is limited	• Main challenges for the market diffusion of biopolymers for coating and packaging are legislation related to standardization and labelling the material and the packaging, the testing and the licencing of the use of new compounds and National and EU policies on the use of primary feedstocks (e.g. residual biomass and agricultural products). • There is lack of a systematic approach towards feedstock because the European biomass production is not optimally organized and tuned to support and align with the bio-based economy developments (Nova Institute 2016). • There is lack of incentives to encourage investment and no specific framework with incentives and support measures for bio-aromatics, similar to that for bioenergy and biofuels (JRC 2016).

biomass (Nova Institute 2016). • Production of bio-based aromatics also requires technologies that are extremely limited at the moment and only available within R&D environment since the technology development in EU is at this stage at small scale (TRL 3-4). • Regarding the algae production and algae products there are tens of thousands of different species globally, but only a handful have been grown commercially. Thus, more research is required at basic science and application level.			

5.1 Advantages of the European biobased industry ecosystem

In the field of bio-based aromatics, Europe has its unique position with outstanding knowhow, research and development of the bio-based molecules. Europe is also strong in the technology development.

Europe has the ecosystem and framework conditions in place conducive to R&D and innovation (Joint Research Center 2016). The following key competitive advantages were identified (KET Observatory 2018): Strong and stable environment for R&D; Solid infrastructure for business support in comparison to the other regions worldwide (which may, however, still be insufficient to meet the demand); Know-how in the field of biotechnologies; Pool of required skills; Availability of the educational institutions to teach the required skills; Environmental consciousness and commitment; Legally stable environment in comparison to other global market such as Asian countries; Good reputation.

6 RECOMMENDATIONS FOR DECISION MAKING

The analysis of the perspective of the 5 different sectors produced the following recommendations for decision making and strategic actions for the public and the private sector, but also for Private Public Partnership (PPP).

6.1 RECOMMENDATIONS FOR PUBLIC POLICIES AND PPP ACTIONS

- Biomass production and supply in Europe must be organized, systematized and optimized (Nova Institute 2016) and a clear role must be identified for each actor along the value chain (Biorizon 2016). With a goal to secure basic and complementary feedstock supply and optimization of the supply chain from within and outside Europe to ensure enough availability at the best price (CEFIC 2001), private-public collaboration is required. The establishment of special bodies at EU and business association levels is proposed with the task to create the interface between public administration and the private sector with the goal to promote a common policy towards a coordinated collaboration and the optimization of the supply chain. Here, important role plays the communication and the availability of the information on the supply needs of the industry on one hand and the availability and strategic planning for the provision of feedstock on the other hand. Then, a structured approach for the analysis of the data produces decisions at strategic and planning level that guarantee the safe, timely and at low cost and high-quality provision of the required feedstock.
- The public sector in collaboration with the private sector has to prepare the chemicals industry for the change to alternative feedstock. This can be achieved by incentivising and engaging large companies as end-users to accelerate the transition to a bio-based economy, by using incentives and policies. Leading examples of large companies working on products derived from bio-aromatic molecules are Ikea (Neste 2016), Coca-Cola (Coka-Cola Company 2015) and Lego (Lego 2015). A strong drive to this direction is the division and enhancement of public procurement policies that favour biobased products accredited for their positive environmental impact against conventional fossil-based products. Also, to discourage the fossil-based product developments and also incentivise the proliferation of the bio-based products the studies suggests that specific measures must be put in place towards this direction; these include the intensification of the CO2 tax, the introduction of tax on fossil-based plastics to account for end-of-life solutions i.e. the introduction of Life Cycle accountability of the companies to the public for their products, combined with financial incentives: e.g. (i) low VAT on bio-based, and adequate subsidies for providing the momentum to the bio-based products but not act as permanent crutches that will cause market distortions; (ii) Sharing best practices, like from Novamont in Italy who are one of the leaders in the BBE must be enabled through networking, (iii) clustering and joint projects and funding.
- A decisive factor the market success of the biobased products, is the market pull described by the consumers preferences towards environmentally friendly products. There, important effect has the increase in public awareness with effect on consumer preferences as a measure of pressure and drive for the market towards bio-based products. To this end targeted campaigns organized by both the public and the private sector can increase public awareness and boost the market uptake of the biobased products. Public funding and economic incentives are finally proposed for encouraging a broader participation of SMEs.

- Algae are on one side recommended for the production of biofuels because they offer the potential of efficient carbon capture and conversion of solar energy to bio-based products including transport fuel largely disconnected from land issues. However, this is possible provided that the specific technological and economic hurdles described in the previous section can be tackled.

- Informing and involving the territorial stakeholders in policy-making process regarding Research and Innovation
- Promoting the consistency of policy and the 'quality' of governance including open dialogue with stakeholders and the public;
- Implementation of regionally adapted bio-based economy policies;
- Developing coordination mechanisms to harmonize policies developed by different ministries, at different levels of governance, including the transnational dimension, and among different sectors. This will increase investors' confidence and stakeholders' motivation to uptake innovative technologies and business models;
- Elaboration of stable, responsible and comprehensive policy and regulatory frameworks to harmonize all the segments of the bio-based value chains through enhanced horizontal (intra- and inter-ministerial) and vertical interaction, involving different levels of governance;
- Coordination between the EC services and different policies not interconnected yet;
- Drafting call topics that specifically address the policy challenges of the bio-based economy;
- National funds for incentives to local governments in order to launch small scale pilot projects for the utilisation of local biomass resources, to meet local community need;

6.2 PRIVATE SECTOR

- Before commercial-scale industrial production can be realized it is required that technology must be developed and upscaled further. Thus, additional investment is suggested for improving and proving technology in industrially relevant environment. Piloting and demonstration of use-cases should be further developed and smaller companies should be also given a wider access to the existing biorefineries. Worth mentioning as a good practice case is BioBase Europe Pilot Plant in Belgium (BBEU 2018). This test facility – as a part of Biorizon (Biorizon 2018)- assists SMEs in overcoming the challenges with regard to the cost, capital equipment and expertise by offering various services such as process development, scale-up and custom manufacturing. Also, BBD has two pilot plants for up-scaling: BBE PP and BPF in Delft. SMEs are helped by Interregional programs such as Bio-based4SME, Biobase NW Europe.

- The value chain must be optimized by integrating the production and the supply chain and promoting the collaboration between the involved actors, thus increasing the added value of the biomass (Star-Colibri 2011). The integration approach is important at this point and includes clustering, facility sharing and collaboration schemes between the actors of the value chain with the most outstanding of them being the biomass producers, the logistics and transportation actors, the biorefineries, and the end wholesale and retail markets. The recommendation for the low price high volume biobased products is the obvious production at large scale in order to achieve economies of scale but this only combined with optimized product mix of biorefineries by including not only the readily and easily marketable drop-in chemicals, for which the downstream supply chain is already in place, but also highly specialized and high value products (ex.: functionalized bio-aromatic compounds, pharmaceuticals and food supplements etc.). Also targeting the highest potential for the utilization of biomass (Nova Institute 2016) is a recommended target. For example, for the production of functionalized aromatics, biomass is valorised in much higher percentage than that for the production of drop-in chemicals, reaching up to 100% biomass utilization for starch polymers and cellulose derivatives (Nova Institute 2016), and may thereby leading to a promising business case. Thus, the use of bio-based aromatic molecules for the production of more sustainable products, such as functionalized aromatics and bioplastics instead of solvents or cleaning agents, will result in better market potential for bio-based aromatics in the longer term (Nova Institute 2016).

- The location and setup of the biorefineries within industrial clusters where all the necessary activities to convert biomass to bio-aromatics take place can play a strategic role in the future development of European bio-aromatics-based production. In this case, location and proximity can play an important role, ensuring an optimal system of diverse industrial activities with **shared** facilities. In the context of circular economy, tapping on the industrial symbiosis potential will bring additional benefits and opportunities for waste reduction and bioproduct productions by setting up biorefineries within industrial clusters with shared facilities. In order to achieve this goal, the network and partnerships of actors along the value chain in EU must be expanded further to include more regions and sectors across the supply chain than for example the existing limited number located around the Antwerp Rotterdam Rhine Ruhr Area (ARRRA) and includes members mostly belonging to the BBD cluster (Biobased Delta 2018).

- Research on the behaviour and properties of unexplored micro-algae species must be reinforced because algae offer the potential of efficient carbon capture and conversion of solar energy to bio-based products including transport fuel largely disconnected from land issues.

- Although new cost reducing strategies for utilizing algae for fuel production will be identified by future research, there is significant economic potential for algae in other applications, some of which can complement the use of algae as fuels resource also. Biorefineries which integrate algae conversion processes and equipment to produce fuels, power, and chemicals from biomass, offer a solution (D-Factory 2017). Much research is needed to optimize the microalgae growth and to develop large-scale food and feed production from algae—one needed to identify species, production, procedures, etc.

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6.2.1 Recommendations to companies related to product mix selection

- For the successful entrance of biobased products in the polymers and plastics market PLA, PEF and PHAs are the flagship bio-products with broad range of applications, cost effective production and superior properties (see Table 3).

- The second study on biobased coating and packaging material concluded the market trend is directed towards monolayer packaging that can be recycled, also to biodegradable packaging, where PLA makes a perfect candidate, but also products which comply with high mechanical, water and heat resistance properties are recommended for a competitive product mix.

- A number of products with the highest market potential have been identified by the study on wood-based products. These include polylactic acid, FDCA, xylitol, xylonate, furfural and the other products listed in Table 14, with FDCA and levulinic acid being the products with the highest potential as they are the precursors of numerous other niche chemicals and substances but also polymers, plastics and other chemicals (see Figure 36).

- The bioaromatics are promising biobased products especially because the market demand for BTX and Phenol is increasing rapidly and this is combined with the significant environmental impact of the production from fossil resources. However, the production of BTX and lignin-based phenol must be combined with the production of functionalized aromatics addressing a higher value product market.

- Algae products have a potential application in food and feed supplements, nutraceuticals, pharmaceuticals, and pollution control. Algae product with good market and economic potential include polysaccharides and omega-3 fatty acids, which they can be marketed through distributional channels of drugs and health products. Several types of polysaccharides and many algal derivatives are irreplaceable. The potential market for microalgae-derived food colouring is also significant. Further, the trend towards addressing higher value markets such as condiments for human food, and inclusion in cosmetics products should be encouraged.

7 CONCLUSIONS

Europe has a number of key competitive advantages compared to other regions worldwide: First, Europe offers strong and stable environment for R&D, and a solid infrastructure for business support in comparison to the other regions. It also possesses a high developed know-how in the field of biotechnologies; It also has a rich pool of required skills and an availability of the educational institutions to teach the required skills. Europe as a whole is environmental conscious and holds a strong political and social commitment for environmental protection and climate change mitigation; It finally has a legally stable environment in comparison to other global markets such as Asian countries; and also has a good reputation as a business partner.

Markets and end products determine the basis for any business. The global market for bioproducts should reach $714.6 billion by 2021 from $466.6 billion in 2016 at a compound annual growth rate (CAGR) of 8.9%, from 2016 to 2021 (BCC RESEARCH 2017). Biomass can be used to make a lot of different products, however significant research is still needed to improve fractionation and industrializing the processes. Large scale and small scale are both very challenging and many potential products need an oil price much higher than today. Markets of high value products are usually too small and growing the volumes often slaughter the price levels.

There is a plethora of potential bio-based products and many have a significant growth potential. Bio-based products can be classified in different ways, and no matter which classification is selected there will remain ambiguities. For example, when considering platform chemicals such as ethanol, a relevant question becomes whether or not to consider it as the final (ethanol as fuel) or as an intermediate product (ethanol as a precursor for ethylene and PE production). Nevertheless, it is apparent from the 5 studies that the portfolio of possible products includes a wide range from high-volume low-price commodities, such as biofuels and bioplastics, to low volume high price substances, such as specialty chemicals for the pharmaceutical industry. The successful commercialisation and diffusion of these products does not depend on technical issues only. For instance, the forestry products industry will have a challenge in introducing wood-based biofuel on the market because corn-based ethanol is currently produced at lower cost partly due to sheer production volume. Besides production costs, market size and competition, also policy instruments affect the competitiveness of different products. For example, in many countries there are currently subsidies when biomass is used for biofuels and bioelectricity production, while this is not the case for the production of green chemicals and materials. Moreover, the environmental impact due to the production of bio-based products needs to be taken into account, when assessing the future desirability of individual products. It is not guaranteed that all bio-based products are more environmentally friendly than the replaced fossil-based products.

Among the most general conclusions is that technology must be further developed and upscaled. Also, complementary feedstock must be secured, and the supply chain must be optimized from within and outside Europe to ensure enough availability at the best price. The goal is to produce large quantities of the new chemical building blocks, but also prepare and support with policies and incentivize the chemicals industry to change towards the use of alternative feedstock. Specifically, the use of bio-based

aromatic molecules for the production of more sustainable products, such as bioplastics instead of bio-fuels, could result in better market potential for bio-based aromatics in the longer term.
The product mix of biorefineries must be optimize by including not only the readily and easily marketable drop-in chemicals, for which the downstream supply chain is already in place, but also highly specialized and high value functionalized compounds.

Policies, strategies and dedicated campaigns must be implemented to increase public awareness with the desired effect on shifting consumer preferences as a measure of pressure and drive for the market towards bio-based products.
Piloting and demonstration of use-cases should be further developed and smaller companies (SMEs) should be also given a wider access to the existing biorefineries and supported by low cost shared experimenting and testing facilities.

8 APPENDIX

Questionnaire for stakeholders

Definition: By "value chain instances" we define the set of specified actual or prospective realizations/manifestations of a general value chain. For example; an instance of the bio-based coating and packaging materials value chain is the first item of Table 1: "Antimicrobial coatings of temperature-stable natural substances with antimicrobial properties derived from plants". Therefore, each instance will be uniquely defined by at least a specific feedstock-process-product chain.

Purpose of the questionnaire: to gather and organize information and data on specific innovative bio-based value chain instances.

Content of the questionnaire: it contains questions related to every stage of the value chain starting from the feedstock and feedstock supply, continuing with processes and technologies, and ending with market and possible impact of each value chain instance.

Purpose of the analysis of data: to assess the technological maturity, the economic feasibility, the environmental impact of the proposed value chain instances. Further, the analysis of the data will identify weak point in the value chain where improvements will be needed. Examples are the technological inefficiencies, financial insufficiency, feedstock unavailability and market immaturity. Based on the findings of the analysis, specific improvement and corrective measures will be proposed to respond effectively to the specific needs.

1. General questions on the description of value chain instances

1.1 What is the main product of this value chain instance?

Please provide:

name(s),

chemical types (where relevant)

state: (liquid, solid, other)

1.2 What is the main application of the product?

Is it an end use (consumable) product or intermediate chemical/substance for other intermediate or end use products? Please describe the application for end products.

1.3 What <u>new</u> applications do the bio-based products have?

2. Questions on feedstocks and upstream supply chain

2.1 What is the main feedstock used for the production of this product?

2.2 What is the spatial, seasonal and quantitative availability of the main feedstock used for the production of this product?

2.3 Does the main feedstock have standardized composition and specifications, and if yes what are they?

2.4 What are the auxiliary chemicals, and utilities used for the production of this product?

(solvents, energy, water)

3. Questions on processes and technology readiness level

3.1 What is the technology readiness level of this bio-based product production process?

(is it at experimental, pilot, demo or industrial scale proven)

3.2 What is the capacity (feedstock) of the process?

(for demo and industrial scale)

3.3 What is the yield of the process?

(please provide overall feedstock to product conversion factors)

3.4 What are the by-products of the process, and what is their use?

3.5 What are the utilities and chemicals consumptions of the process?

(per kg of product)

3.6 Does the process possess superior from environmental perspective characteristics compared to other processes?

(lower energy, water, chemicals consumption) If yes, please provide comparison against conventional or other process

4. Questions on markets and downstream supply chain

4.1 What new or existing consumer needs the bio-based products will cover?

4.2 What is the forecasted demand for the bio-based products?

4.3 What is the geographical (European and worldwide) distribution of the current and forecasted demand?

4.4 What conventional products are replaced by the bio-based products?

chemical types (where relevant)

4.5 What is the potential market share of the bio-based products?

4.6 Is there an existing supply chain for the market distribution of the products or does a new one has to be build?

4.7 What are the relevant distribution channels that are/will be used?

5. Questions on societal and environmental impact

5.1 What is the potential for job creation quantitatively (per tonne of product/year) along the value chain?

5.2 What is the environmental benefit/impact of the value chain?

5.3 Questions on stakeholder identification and definition of stakeholder relationships

5.4 Who are the necessary stakeholders for the formulation of the value chain instance?

(define stakeholders from each stage; feedstock supply, logistics, production process, end or intermediate market, finance, etc.)

5.5 What are the requirements from and role of each stakeholder inside the value chain?

5.6 What are the relationships between the stakeholders?

1. Questions on policy, funding and financial issues

6.1 Is there relevant EU policy in place?

6.2 What are the possible funding channels and means?

6.3 Is the value chain overall profitable?

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