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1 **Lignocellulosic biorefineries in Europe: current state and prospects**

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22 **Abstract:**

23 Lignocellulosic biorefining processes plant-derived biomass into a range of bio-based
24 products. Currently, more than 40 lignocellulosic biorefineries are operating across Europe.
25 We address the challenges and future opportunities of this nascent industry by elucidating
26 key elements of the biorefining sector, including feedstock sourcing, processing methods, and
27 the bioproducts market.

28

29 **Keywords:** Bioeconomy; Sustainability; Biorefinery; Lignocellulose; Bioenergy;
30 Bioproducts

31

32 **1. The Biorefinery Industry in the EU**

33 In 2012, the European Bioeconomy strategy was launched, defining the bioeconomy as "the
34 production of renewable biological resources and the conversion of these resources and waste
35 streams into value added products". This strategy and its action plans increased the turnover
36 of the total bioeconomy in the EU from 2.09 trillion Euro in 2008 to 2.29 trillion in 2015 [1].
37 In the light of this development, the biorefinery is a vital component of the future
38 bioeconomy defined by the International Energy Agency (IEA Bioenergy -Task 42, 2009) as
39 "an integrated production plant using biomass feedstock to produce a range of value-added
40 products". In 2017, there were 224 biorefineries operating across Europe, in addition to
41 several currently under construction [2]. However, 181 of these commercial biorefineries are
42 so-called first-generation facilities, which use feedstocks such as sugar, starch, oils and fats,
43 and produce mainly biofuels and products of oleochemistry. Conversely, only 43
44 biorefineries are so-called second-generation facilities, which use more sustainable
45 lignocellulosic feedstocks, such as non-food, non-energy crops and bio-waste, to produce
46 biofuels, electricity, heat, bio-based chemicals and biomaterials. Fast-paced regulatory

47 developments in the EU are accelerating the rate of lignocellulosic exploitation. For example,
48 EU Directive 2015/1513 set out targets for a maximum of 7% share of biofuels to be derived
49 from cereals, starch, sugars and oil-bearing crops by 2020 (including those grown for energy
50 purposes on agricultural land). Additionally, in January 2018, the European parliament voted
51 to limit its support for biofuels made from food crops, aiming to gradually reduce such fuels
52 to 3.8% by 2030; ancillary measures seek to exclude palm oil-derived biofuels from the list of
53 products that can count towards renewable targets by 2021, and to incentivize the use of
54 lignocellulosic wastes in biofuel production. The EU has funded many projects under
55 Horizon 2020 (the EU Research and Innovation programme that manages about €80 billion
56 of research funding over the 7-year period from 2014 to 2020) to stimulate the use of various
57 lignocellulosic feedstocks, with the aim of consolidating lignocellulosic-based biorefineries
58 in Europe (Table 1). Therefore, a critical assessment of the future of the lignocellulosic
59 biorefinery concept against a background of the current biorefining industry is especially
60 timely.

61 **2. The workflow of biorefining industry:**

62 **2.1. Lignocellulosic Feedstock Supply**

63 Many different raw materials can be used as feedstocks for a lignocellulosic biorefinery, from
64 residues derived from forestry or agriculture to agro-industrial wastes. The current annual
65 consumption of lignocellulosic biomass in bio-based industries, as compared to total biomass
66 availability, is relatively small. Even future projections, such as estimates outlined in the
67 S2Biom project (which aims to predict the sustainable non-food biomass potential at the EU
68 level), have predicted a maximum requirement of 476 million tons of lignocellulosic biomass
69 to fulfil the needs of all bio-based industry in Europe by 2030. To put this into perspective, at
70 least 1 billion tons of lignocellulosic biomass will be produced in Europe on an annual basis
71 by 2030 [3]. Therefore, the challenge is not the availability of feedstock, but rather the

72 logistical challenge surrounding the feedstock supply. The lignocellulosic feedstock supply
73 chain may encompass collection, drying, densification, transport, and storage, and such
74 processes will vary depending on biomass type and source [4-6]. Each supply chain stage
75 faces formidable challenges, which can be summarized as follows:

76 **Collection:** The greatest challenges in the collection process are the marked decentralization
77 of sources, the unpredictable fluctuations in quantity and quality, high moisture content (e.g.
78 in case of agro-industrial waste) and possible contamination (e.g. soil pollution in agricultural
79 residues). Collection, drying and densification are conducted in decentralized facilities prior
80 to transportation to the biorefinery or centralized storage facility.

81 **Drying:** Lignocellulosic biomass derived from agro-industrial wastes/residues contains a high
82 level of moisture, which may complicate biomass handling, size reduction and densification,
83 as well as increasing the susceptibility of biomass to spoilage and a consequent rapid
84 deterioration in quality. Drying processes may be natural (e.g. in the case of grasses) or
85 conducted via conventional heating or microwaves.

86 **Densification:** Densification (compaction), carried out by means of stacking, baling,
87 briquetting, or pelletizing, is an essential pre-processing step to increase the bulk density of
88 lignocellulosic materials. These steps permit efficient transport and storage operations and
89 achieve standard sizes and weights for each unit of feedstock. Before the compacting process,
90 mechanical processing may be required to reduce size by shredding and grinding. While
91 existing equipment used in agriculture could be employed in moderate-scale biomass
92 compacting and size reduction, new technologies are required to handle large amounts of
93 biomass for industrial scale processing.

94 **Transport:** Economically, transportation efficiency is increased when the collection area is
95 closer to the processing/storage facility. Existing transportation systems employed for

96 moving woodchips or lignocellulosic wastes may prove inefficient due to the low density of
97 lignocellulosic wastes and transportation energy costs.

98 **Storage:** Variations in quantity and seasonal availability of agricultural residues or agro-
99 industrial waste, as well as in the location of sources, all combine to create the need for long-
100 term storage facilities. However, this requirement presents challenges in terms of maintaining
101 biomass quality at a high capacity and at a low cost. Additionally, there may be significant
102 health and safety aspects of biomass storage that can complicate operations [7].

103 To address these challenges in supply chain logistics, several strategic research initiatives
104 have been recommended by The European Biorefinery Joint Strategic Research Roadmap for
105 2020, with a view to achieving the European Biorefinery 2030 vision [8]. Such
106 recommendations include the development of integrated logistical models to remove supply
107 chain bottlenecks, the availability of machinery which is capable of handling large amounts
108 of feedstock, the mapping of biomass inventories, and the establishment of a centralized
109 regional hub for biomass collection and storage.

110 These efforts are expected to decrease logistical costs, which in turn may reduce biorefinery
111 production costs. However, for long-term commercial success, economies of scale in terms of
112 biorefinery size are also vital in the goal to achieve economically acceptable conversion
113 processes [9]. Thus, logistics costs and operational complexity increase as processing
114 capacity or lignocellulosic feedstock collection/storage radius increase. Accordingly, smaller-
115 scale integrated biorefinery units are being studied for suitability in small rural-urban areas in
116 Europe to address these challenges [10].

117 **2.2. Processing of Lignocellulosic Feedstock:**

118 **Current lignocellulose pretreatment approaches:** Lignocellulosic biomass is a complex
119 matrix that is relatively refractory to degradation. Sugars are locked in a recalcitrant structure

120 that requires a pretreatment step to release them. Many conventional methods (e.g. chemical,
121 physical, and biological methods) are used for pretreating lignocellulosic biomass. However,
122 achieving a workable balance between pretreatment efficacy, cost and environmental
123 sustainability is difficult [11]. Therefore, even combinations of these methods have not been
124 deployed effectively at the required scale of an integrated biorefinery that utilizes multiple
125 feedstocks.

126 **Current lignocellulose utilization technologies:** The current mainstream lignocellulose
127 disruption technologies that are employed in a typical biorefinery depend both on the specific
128 lignocellulosic feedstock and the value of the final product. Such technologies may be
129 classified as either biochemical [12] or thermochemical [13], and key challenges relate to
130 scalability and flexibility to sustainably optimize the production process (against a
131 background of diverse feedstocks, variable market demand and fluctuating economics).
132 Hence, integrating the biorefinery concept with existing industrial processing methods has
133 been identified as a potential solution to address these challenges. For example, the most
134 common proposed model cited is an integrated biorefinery-pulp/paper plant that can produce
135 chemicals, fuels, or electric power, along with conventional wood, pulp, and paper products.
136 However, in reality, aspects such as the separation and purification of products, as well as
137 ensuring quality and standardization, add additional challenges to the industrialization
138 process.

139 **2.3. Biobased products market**

140 Examples of potential bio-based products include biofuels (e.g. bioethanol, biodiesel, and
141 biogas), biochemicals (e.g. industrial enzymes, and nutraceuticals), and biomaterials (e.g.
142 biodegradable plastics) [14]. However, supported by specific EU policies (Fig. 1), bioenergy
143 and biofuels have received greater attention. By the year 2030, the EU aims to provide 25%

144 of its transportation energy via biofuels derived from advanced biorefineries (2nd generation
145 biorefineries). By this time, it also intends to replace 30% of oil-based chemicals by bio-
146 based chemicals, and supplant non-degradable materials with degradable materials.
147 Interestingly, 80% of the EU bio-based infrastructure will be in rural areas, which are
148 expected to support community development programs. However, developing sustainable
149 markets for bio-based products, and raising the public awareness of this area will still be a
150 challenge. Even so, it is expected that evolving market demand, combined with further EU
151 policies acting to spur public awareness, will accelerate product development and encourage
152 private sector investment. International experts foresee that at least 15 advanced biorefineries
153 will be launched by 2024 [15].

154 **3. Conclusion**

155 The lignocellulosic biorefinery represents an important component of the future European
156 bioeconomy. While this nascent industry faces significant challenges, such as feedstock
157 logistics, limitations of conventional processing technologies and uncertain market
158 economics, such challenges are being countered by ambitious EU policies that are aimed at
159 supporting this industry to achieve climate and bioenergy goals.

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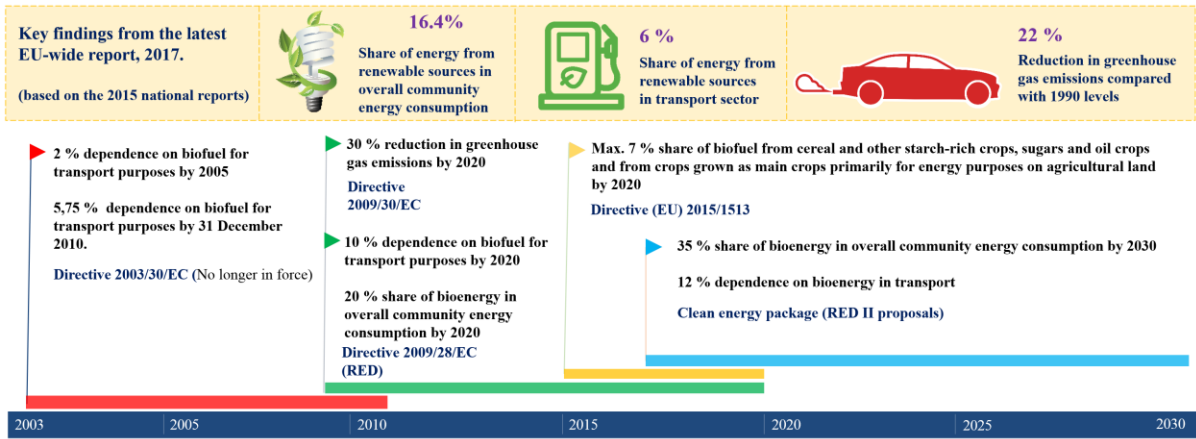
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212 Table 1. Funded projects by the EU for utilizing Lignocellulosic feedstock in Biorefinery industry.

Project name	Biorefinery Feedstock	Coordinated in	Period	Total Cost (EUR)
AgriChemWhey	By-products from dairy processing	Ireland	2018-2021	29 949 323
GRACE	<i>Miscanthus</i> or hemp varieties from marginal lands	Germany	2017-2022	15 000 851,21
SmartLi	Kraft lignins, lignosulphonates and bleaching effluents	Finland	2015-2019	2 407 461,25
BIOSKOH	Lignocellulosic feedstock	Italy	2016-2021	30 122 313,75
BARBARA	Agri and food waste	Spain	2017-2020	2 711 375
AgriMax	Agri and food waste	Spain	2016-2020	15 543 494,56
PULP2VALUE	Sugarbeet Pulp	Netherlands	2015-2019	11 428 347,50
GreenSolRes	Lignocellulosic residues or wastes	Netherlands	2016-2020	10 609 637,01
Dendromass4Europe	Dendromass on marginal land	Germany	2017-2022	20 442 318,75
SYLFEED	Wood residues	France	2017-2020	14 976 590
GreenProtein	Vegetable residues from the packed salad processing	Netherlands	2016-2021	5 546 519,99
PROMINENT	Cereal processing side streams.	Finland	2015-2018	3 103 897,50
FIRST2RUN	Cardoon from marginal lands	Italy	2015-2019	25 022 688,75
Zelcor	Lignocellulosic residues from ethanol production, lignins dissolved during pulping process and lignin-like humins formed by sugars conversion	France	2016-2020	6 710 012,50
STAR4BBI	Lignocellulosic feedstocks from forests, and agriculture	Netherlands	2016-2019	995 877,50
BIOrescue	Wheat straw and agri-industrial waste	Spain	2016-2019	3 767 587,50
OPTISOCHEM	Residual wheat straw	France	2017-2021	16 376 816,83
US4GREENCHEM	Lignocellulosic feedstock	Germany	2015-2019	3 803 925
FUNGUSCHAIN	Mushroom (<i>Agaricus bisporus</i>) farming residues	Netherlands	2016-2020	8 143 661,25
POLYBIOSKIN	Food waste	Spain	2017-2020	4 058 359,38
ValChem	Woody feedstock	Finland	2015-2019	18 502 703,25
LIBBIO	Andes Lupin from marginal lands	Iceland	2016-2020	4 923 750
LIGNOFLAG	Straw	Germany	2017-2022	34 969 215



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214 Figure 1. Biofuel Policy and Targets from 2003 to 2018; Road map for 2020 and beyond

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