Biorefinery: Concepts, Current Status, and Development Trends

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BIOREFINERY : CONCEPTS, CURRENT STATUS, AND DEVELOPMENT TRENDS

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Abstract

Biorefineries are expected to effectively utilise abundant biomass resources in a sustainable manner in order to ensure energy security, mitigate climate change, and meet the endless demand for chemicals and materials. This paper reviews the current global status and developmental trends in the field of biorefinery. To date, the biorefinery industry is mainly in the pilot and demonstration stages. Considerable developmental work is underway, and new biorefinery concepts are expected to be commercially deployed by 2020. The deployment of biorefineries, based largely on lignocellulosic feedstock, depends on the technical maturity of a range of production processes. The combination of market formation and governmental support for biomass-derived products is one of the important factors in determining the type and rate of biorefinery deployment.

Keywords: Biomass; Biorefinery; Feedstock; Lignocellulosic; Pilot.

1. Introduction

Biorefinery is similar to petroleum refinery except that it utilises biomass instead of crude oil to produce transportation fuels, heat, power, chemicals, and materials. Because biomass is renewable and carbon-neutral, at the World Economic Forum in 2008 and 2009, the use of industrial biorefineries was identified as one potential solution that may help to mitigate the threat of climate change and meet the seemingly boundless demand for energy, fuels, chemicals and materials [1].

A schematic description of the biorefinery processes is shown in Fig. 1. The biorefinery is not a completely new concept. The sugar, starch, pulp and paper industries that use traditional conversion processes are called phase I-biorefineries [2]. However, several environmental and economic forces such as global warming, security of energy and food supply, high energy costs, and agricultural policies have also directed those industries to further evolve their operations into biorefineries that sustainably produce a spectrum of chemicals, materials and bioenergy. In some reports, phase I-biorefineries do not meet the new concepts of biorefinery. To date, biorefineries are at the conceptual stage for many countries in the world, with new products and production processes still being identified. There are different definitions being used depending on the type of activity and stakeholders involved.

The purpose of this review paper is to introduce new biorefinery concepts and classifications, to summarise the current status and developmental trends of biorefineries based on the published reports of IEA Bioenergy Task 42, Bioenergy Euroview, and the U.S. Department of Energy Report on Integrated Biorefineries. Furthermore, the review introduces ideas regarding how to promote the deployment of commercial-scale biorefineries. Parts of the texts, tables and figures in this study were directly copied from previously published papers and reports.

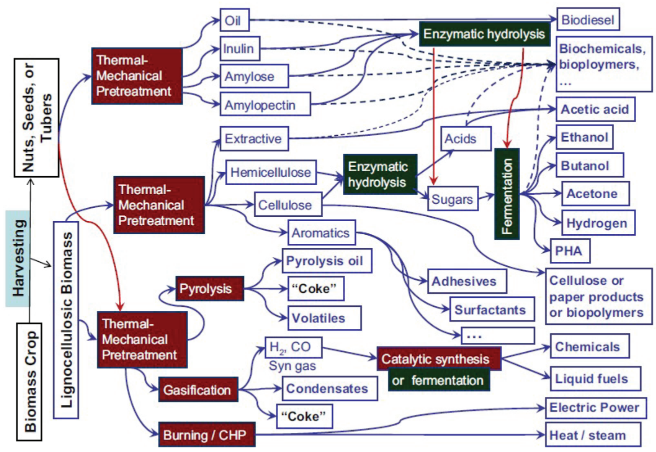

Fig. 1. A schematic description of biorefinery processes [5].

2. Definition and Classification System of Biorefinery

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2.1. Definition [3, 4]

Depending on the type of activity and stakeholders involved, many different definitions for biorefinery are currently being used. Some examples are as follows :

- A biorefinery is *a facility* that integrates biomass conversion processes and equipment to produce fuels, power, and value-added chemicals from biomass (NREL, 2007).
- A biorefinery is *a cluster of bio-based industries* producing chemicals, fuels, power, products, and materials.
- A biorefinery is a refining facility where biomass is converted into fuel, chemicals, materials and other uses, all at the same plant (Bio-fuels for Transport, Worldwatch Institute, 2006).
- A biorefinery is *an overall concept* of a promising plant where biomass feedstocks are converted and extracted into a spectrum of valuable products (DOE, 2007).
- Biorefinery is *the separation of biomass* into distinct components that can be individually brought to the market either directly after separation or after further (biological, thermochemical, chemical) treatment(s) (Elbersen *et al*., 2003).
- Biorefining is the transfer of the efficiency and logic of the fossil-based chemistry and the substantial converting industries, as well as the production of energy, to the biomass industry (Kamm *et al*., 2006).
- Biorefinery is the concept of converting plant-based biomass to chemicals, energy and materials that may run out in our civilisation, replacing the needs for petroleum, coal, natural gas and other non-renewable energy and chemical sources (Liu S, *et al*., 2011).
- Biorefineries are integrated bio-based industries, using a variety of technologies to produce chemicals, biofuels, food and feed ingredients, biomaterials (including fibres) and power from raw biomass materials (EU Biorefinery Euroview, 2007).
- Biorefinery is *the efficient use of the entire potential of raw materials and by-streams* of the forest-based sector towards a broad range of high value-added products (by cooperation in between chains) (Biorefinery Taskforce FTP, 2007).
- A biorefinery is *an integrated cluster of bio-industries*, using a variety of different technologies to produce chemicals, biofuels, food ingredients, and power from raw biomass materials (Europabio, 2007).
- Definition of biorefinery within the framework of IEA Bioenergy Task 42 :

"*Biorefinery is the sustainable processing of biomass into a spectrum of marketable products and energy*" - This definition had been used as the framework for the BIOPOL final report and Status Report Biorefinery 2007 [2, 3]. With this definition, biorefineries are expected to supply a wide range of bio-based products and energy in a socioeconomically and environmentally sustainable manner.

The mentioned definitions include the following key words :

- Biorefinery: concepts, facilities, processes, cluster of industries
- Sustainable: maximising economics, minimising environmental aspects, replacing fossil fuels, taking socioeconomic aspects into account
- Processing: upstream processing, transformation, fractionation, thermochemical and/or biochemical conversion, extraction, separation, downstream processing
- Biomass: crops, organic residues, agro-residues, forest residues, wood, aquatic biomass
- Spectrum: more than one
- Marketable: a market (acceptable volumes & prices) already exists or is expected to become available in the near future
- Products: both intermediates and final products, i.e., food, feed, chemicals, and materials
- Energy: fuels, power, heat

2.2. Biorefinery Classification System

To date, a clear system to classify the different biorefinery concepts is still lacking. The followings are biorefinery classification systems developed by different organisations.

2.2.1. Biorefinery classification system used in Status Report Biorefinery 2007

Biorefinery concepts are being classified based on feedstock, type of technology, status of technology (first- and second-generation biorefinery), and intermediate (syngas platform, sugar platform, etc.) [3].

Seven different biorefinery concepts are presented as follows :

- Conventional Biorefineries (CBR)
- Green Biorefineries (GBR)
- Whole Crop Biorefineries (WCBR)
- Lignocellulosic Feedstock Biorefineries (LCFBR)
- Two Platform Concept Biorefineries (TPCBR)
- Thermo Chemical Biorefineries (TCBR)
- Marine Biorefineries (MBR)

Conventional Biorefineries (CBR): Many existing industries fall under the category of conventional biorefineries: the sugar industry (beet, cane), the starch industry (wheat, cassava, potato), the vegetable oils industry (soy, rape seed), the feed industry, the food industry, the pulp and paper (forest) industry, the (petro) chemical industry, and the conventional biofuel industry (biodiesel, bioethanol, biogas). However, these industries concentrate on producing their main products, and no great efforts have yet been made to produce a broad spectrum of other value-added products such as biochemicals or biofuels. Thus, this type of biorefinery does not meet the definition of the new biorefinery concept. In many cases, an extension of a conventional biorefinery will form the basis for the development of one of the newer six types of biorefineries (see Table 1).

Table 1. Summary of characteristics of the biorefinery concept

Concept	Type of feedstock	Predominant technology	Phase of development
Green Biorefineries (GBR)	wet biomass: green grasses and green crops, such as lucerne and clover	pretreatment, pressing, fractionation, separation, digestion	Pilot Plant (and R&D)
Whole Crop Biorefineries (WCBR)	whole crop (including straw) cereals such as rye, wheat, and maize	dry or wet milling, biochemical conversion	Pilot Plant (and Demo)
Ligno Cellulosic Feedstock Biorefineries (LCFBR)	lignocellulosic-rich biomass: e.g. straw, chaff, reed, miscanthus, wood	pretreatment, chemical & enzymatic hydrolysis, fermentation, separation	R&D/Pilot Plant (EC), Demo (US)
Two Platform Concept Biorefineries (TPCBR)	all types of biomass	combination of sugar platform (biochemical conversion) and syngas platform (thermochemical conversion)	Pilot Plant
Thermo Chemical Biorefineries (TCBR)	all types of biomass	thermochemical conversion: torrefaction, pyrolysis, gasification, HTU, product separation, catalytic synthesis	Pilot Plant (R&D and Demo)
Marine Biorefineries (MBR)	aquatic biomass: microalgae and macroalgae (seaweed)	cell disruption, product extraction and separation	R&D (and Pilot Plant)

2.2.2. Biorefinery classification system by IEA Bioenergy Task 42

IEA Bioenergy Task 42's approach to biorefinery classification considers four main features, which are able to identify, classify and describe the different biorefinery systems: *platforms, products, feedstocks, and conversion processes* [4], (Fig. 2).

The platforms (*e.g.*, C5/C6 sugars, syngas, biogas) are intermediates that are able to connect different biorefinery systems to their processes. The number of involved platforms is an indication of the system complexity. The two biorefinery product groups are energy products (*e.g.*, bioethanol, biodiesel, and synthetic bio-fuels) and material products (*e.g.*, chemicals, materials, food and feed). Feedstocks can be grouped as either energy crops from agriculture (*e.g.*, starch crops, short rotation forestry) or biomass residues from agriculture, forestry, trade and industry (*e.g.*, straw, bark, used cooking oils, waste streams from biomass processing). Concerning conversion processes, the classification system identifies four main groups, including biochemical (*e.g.*, fermentation, enzymatic conversion) [indicated in Fig. 2 as orange squares], thermochemical (*e.g.*, gasification, pyrolysis) [yellow squares], chemical (*e.g.*, acid hydrolysis, synthesis, esterification) [blue squares] and mechanical processes (*e.g.*, fractionation, pressing, size reduction) [white squares]. The biorefinery systems are classified by quoting the involved platforms, products, and feedstocks. Some examples of classifications are:

- ´C6 sugar platform biorefinery for bioethanol and animal feed from starch crops´
- ´Syngas platform biorefinery for FT-diesel and phenols from straw´
- ´C6 & C5 sugar and syngas platform biorefinery for bioethanol, FT-diesel and furfural from sawmill residues´

An overview of current platforms, products, feedstocks and conversion processes is given in Fig. 2. This system is expected to evolve as new technologies are developed and additional platforms are defined.

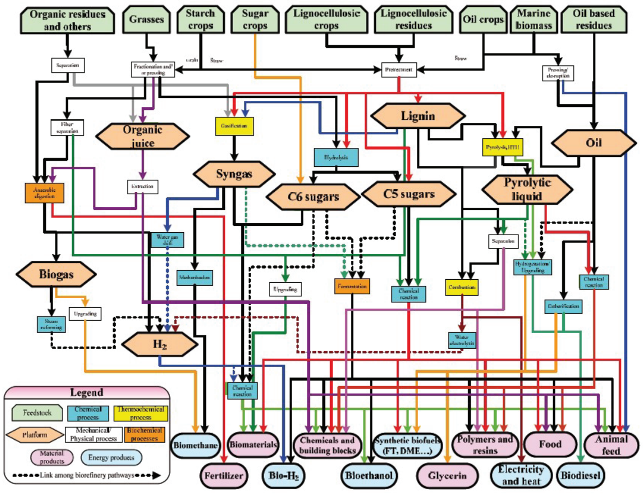

Fig. 2. Overview of the biorefinery classification system

3. Current Status and Developmental Trends of Biorefineries

According to the literature, the current status of biorefineries in Europe and the United States (USA) is used as the global standard. This part provides an overview of both existing and planned biorefinery facilities and a description of pilot and demonstration biorefinery projects in Europe and the USA, as biorefinery is still a novel concept for the rest of the world.

3.1. In Europe

Information from the BIOPOL and BIOREFINERY EUROVIEW projects [6], which was obtained through a survey based on a joint questionnaire that was developed in cooperation by the BIOREFINERY EUROVIEW (WP1 "State of the art of existing biorefineries" and WP2 "State of the art of socioeconomic impacting factors") and BIOPOL (WP2 "assessment of social and environmental implications" and WP4 "Review of current implementation status") project consortia, has been reported. The questionnaire was sent to 2800 industrial stakeholders in 16 EU countries plus Norway, Switzerland and the USA. A total of 110 returned questionnaires from 11 countries were used for mapping and further analysis. In the survey, from a total of 110 industrial sites in Europe, there were 34 existing or planned biorefineries. These biorefineries are based on different concepts from cereal biorefinery, whole crop biorefinery, oilseed biorefinery, green biorefinery, lignocellulosic feedstock / forest-based and lignocellulosic biorefinery, and multiple feed / integrated biorefinery as defined in the BIOPOL and EUROVIEW projects. The majority of the identified biorefineries are located in Western Europe (23), followed by Northern (8) and Southern Europe (3). No existing biorefineries were identified in the Eastern EU countries (Fig. 3). Additionally, the majority of the identified biorefinery-related R&D, pilots and demonstration projects take place in Western Europe (28), followed by Northern Europe (16) and Southern Europe (1). No biorefinery-related R&D, pilots, and demonstration projects were identified in the Eastern European countries.

Approximately 75 % of the biorefinery sites are located within an area comprising Northern France, Germany, Denmark, Belgium, the Netherlands, and the UK. These six countries have a variety of suitable feedstocks and an intensive (petro) chemical industry. The mapping results confirm a positive correlation between existing and planned biorefineries and the occurrence of chemical industries, biofuel industries and agro-industries in mainly the starch and sugar sectors, due to the availability of the wheat and sugar beet feedstocks.

Oilseed biorefineries seem currently less developed in the EU27+, in spite of a large production of oil seed crops that seem to be used mostly for biodiesel production. To date, a substantial number of biorefinery plants and projects using a range of feedstocks are operational in the EU27+ or can be expected to be realised in the short term.

A relatively high number of green biorefineries using grass as feedstock (7) was identified, given that grass can be considered a second-generation feedstock that requires innovative processing technology. Furthermore, a substantial number of current and planned lignocellulosic feedstock biorefineries (11) were identified that are positively correlated with the availability of wood (including forestry residues) and straw. Based on feedstock availability, there is a large potential for the expansion of these advanced concepts.

The sites with more than one colour relate to multiple feed / integrated biorefineries, according to the EUROVIEW definition. The mapping of the availability of specific feedstocks in the EU27+ shows that several Eastern European countries have high potential for biorefinery based on feedstock availability. The fact that no biorefineries or biorefinery-related R&D, pilots and demonstration projects were identified in one of these countries seems to imply that in addition to feedstock availability, other factors such as a good infrastructure and the presence of petrochemical industries are required for the development of biorefinery plants.

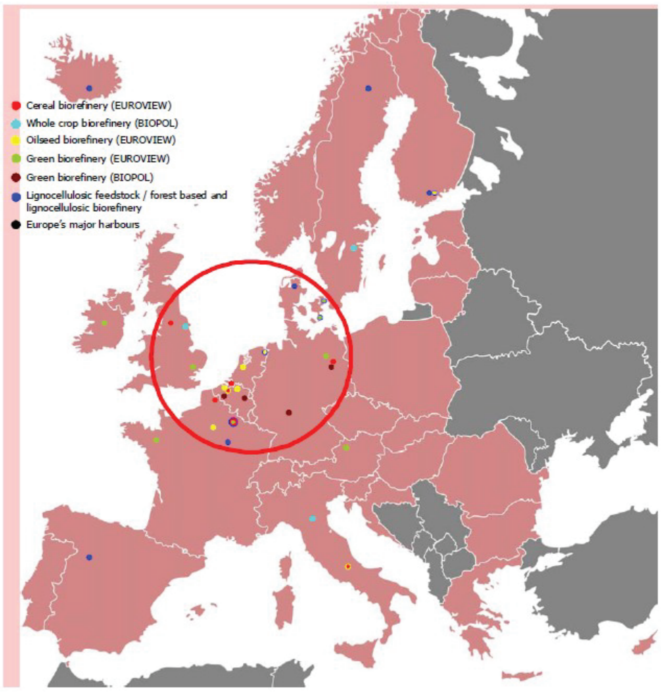

Fig. 3. Existing or planned biorefineries in Europe

3.2. In the United States

Fig. 4. Location of Integrated Biorefinery Projects Receiving DOE Funds [7]

The U.S. is the leading country in the promotion of deploying biorefineries. The U.S. biorefinery initiative has been established in a number of presidential directives and legislation. The following two goals have been recently set [8]:

- The Advanced Energy Initiative (2006) established a goal to make the prices of cellulosic ethanol competitive with those of corn ethanol by 2012 (Bush 2006).
- The Energy Independence and Security Act of 2007 established a renewable fuel standard requiring 36 billion gallons of renewable fuels by 2022. This is nominally 15 % of total petroleum use in the United States and nearly 25 % of imported oil.

In the United States, four government agencies provide the bulk of research funding through competitive grants: the U.S. Department of Energy (DOE), the National Science Foundation (NSF), the U.S. Department of Agriculture (USDA), and the National Institutes of Health (NIH). The DOE Biomass Program works in partnership with industry to develop, build, operate, and validate integrated biorefineries at various scales (pilot, demonstration, and commercial)(Fig. 4).

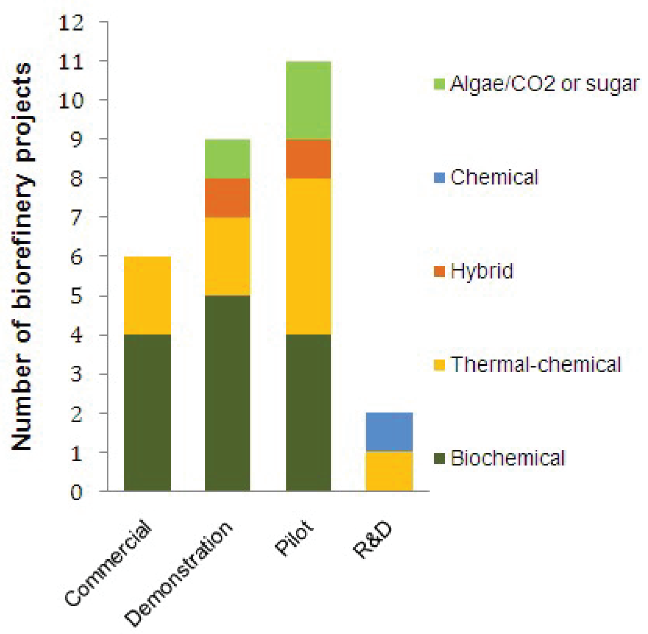

Fig. 5. Integrated biorefinery projects receiving DOE funds

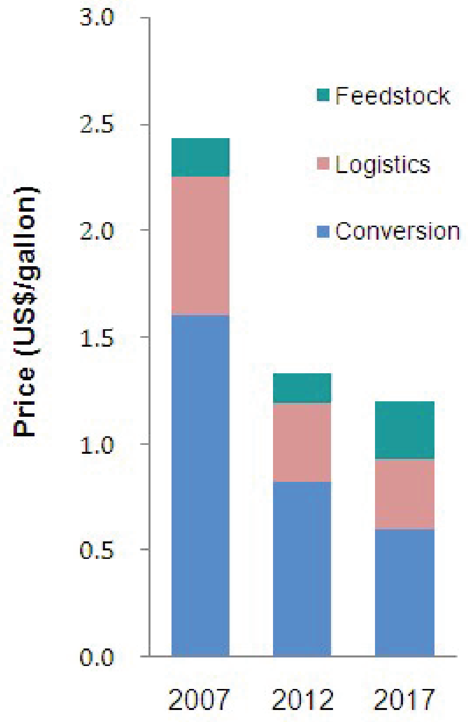

Fig. 6. DOE projected production costs to make ethanol competitive with petroleum by 2012

Figures 5 and 6 were produced from the US/DOE report and websites [7, 9]. From 2007 to June 6, 2012, a total of 29 biorefinery projects have received grants from the DOE for the purpose of building facilities or plants (Fig. 5). These projects received approximately 30 million USD of funding for the demonstration plants and up to 80 million USD for building the commercial plants, some of these plants being located with existing corn ethanol plants or existing petroleum refineries. Approximately 82 % of the projects (25 projects) use lignocellulosic feedstock to produce ethanol, renewable fuels and other products via biochemical, thermochemical, and hybrid conversion processes. Of the total projects, 50 % (15 projects) have produced ethanol as the primary product, and a biochemical conversion process is popularly applied. So far, biofuels are considered to be the primary products of biorefineries in the U.S. In 2008, the DOE had projected a cost timeline for cellulosic ethanol to make it competitive with petroleum by 2012 (Fig. 6). It was predicted that the production cost for cellulosic ethanol would be at $1.33/gal in 2012 and would drop to $1.2/gal in 2017. Currently, the U.S government has provided an incentive of $1.01/gal for the production of second-generation renewable fuels [8].

4. Developmental Trends of Biorefineries [4, 10]

New concepts of biorefineries involve producing a broader range of materials and chemicals from the rich variety of biomasses. These biorefinery concepts are mostly in R&D, pilot or small-scale demonstration phases, which are far from commercialisation. New biorefinery concepts are expected to be implemented in the market within a few years (2013-2020), and some biorefineries can be expected to be introduced in a variety of market sectors within the next year (up to 2013) by upgrading existing industrial infrastructures. However, current economic conditions (the credit crisis and recessions in parts of the global economy) could severely slow down this market implementation.

For the successful market implementation of an integrated biorefinery concept, all process unit operations must be technically mature, and the full biomass-to-products chain must have no adverse environmental impacts and be economically profitable. Except in cases where organic residues are used as feedstock, biomass production should be part of the development and implementation of integrated biorefinery concepts. Specific biomass crops are being developed to produce a maximum number of products using a minimum number of inputs (*e.g.*, fertiliser and energy). Because of the variety of biorefinery concepts and the variations in maturity of the composing sub-processes, a financial support framework should be long term, extending from R&D activities and continuing through pilot-plant activities, demonstrations, and the development of deployment strategies.

Initiatives presented in this report follow a resource-based approach, where the potential products made from a particular feedstock are the focus. An alternative approach may be to design chemicals and materials together with their production methods that fit the application of the product in a backward integrated petrochemical industry. It is thought that while the resource-based approach fits current petrochemical business and production models, the design-based approach will lead to a real transition in the areas of production and design of chemicals and materials. This backward integrated approach will be immediately applicable in specialty chemical markets, and there may be long-term opportunities in bulk markets.

The mix of market and governmental support for green materials and chemicals and for bioenergy will be an important factor in determining the type and rate of deployment of biorefineries.

5. How to Promote the Deployment of Commercial-scale Biorefineries

To successfully implement commercial-scale biorefineries, numerous technical, strategic, commercial, and sustainable challenges need to be overcome [1, 8].

5.1. Technical challenges

Technical challenges include covering feedstock yield, advanced technologies for lignin utilization, enzyme improvements, microbial cell factories, and processing and logistics:

- ***Feedstock yield and composition of biomass.*** It is crucial to improve the feedstock yield and the composition of biomass for optimal conversion efficiency. This involves plant genomics, breeding programs and the chemical engineering of desirable traits. By making feedstock more robust, further improvements can be made to the economics and security of feedstock availability around the year.
- ***Advanced technologies for lignin utilization.*** Lignin waste is the major residue from biofuel plants, since lignin constitutes up to 30 % of the weight and 40 % of the energy value of biomass. Up to date this lignin is simply exploited by combustion to generate energy for the plants. Due to its chemical structure, a phenolic hetero-polymer, it can be converted to more value added products, such as: carbon fiber, adhesives, phenolic resin, aromatics, etc. as useful materials and chemicals in many industries. The technologies for producing these products from lignin have been researched and trial produced in some research institutions, biorefineries. The advanced improvements in these technologies are inevitable to the success of biorefinery industry.
- ***Efficient enzymes.*** A related technical challenge is the need to develop more efficient and robust enzymes, particularly for the conversion of lignocellulosic material from a variety of feedstock such as corncobs, stover, wheat straw, bagasses, rice, and woody biomass. Additionally, utilisation of a larger part of the biomass will require new processes that allow for the conversion of materials to extract their maximum value.
- ***Microbial cell factories***. A further yield-related challenge is the need to develop microbial cell factories that produce a desired product in a high yield and with high productivity. Further novel heterogeneous catalysis technologies are also needed to transform the chemical intermediates into commercial products.
- ***Processing and logistics.*** The second group of technical challenges relates to the optimisation of feedstock processing and logistics. This includes a number of different areas, such as developing densification techniques that allow the transport of originally low-density feedstock at low cost, establishing preservation techniques to control physical and chemical modification of biomass during pre-conversion processing (i.e., harvesting, storage, transportation), and setting up a bio-based product distribution network that can use the existing infrastructure, *e.g.*, using oil pipelines or upgrading petrol stations to allow the distribution of a higher share of biofuels.

5.2. Commercial and strategic challenges

The commercial challenges facing the industrialisation of bio-products fall into three main categories: issues with integration into existing value chains, funding difficulties and other challenges related to the uncertainty associated with a novel, unconventional field. There are bio-based products that are novel or that cannot easily be integrated into existing value chains; for example, bioethanol can only be mixed into conventional fuel up to a volume share of approximately 15 % without modification of a standard engine. Other commercial hurdles include the inability to obtain a price premium for bio-based products when compared to conventional petroleum-based products and insufficient, uncertain public incentives.

5.3. The sustainability challenge

The motivations for switching to the production of bio-based products include the conservation of resources and environment protection; therefore, the implementation of biorefineries must not jeopardise the environment. The following issues are of the most concern: *land-use change and its effect on GHG emissions and food security.*

- Direct land-use change (DLUC) occurs if feedstock for biorefinery purposes (e.g., soybean for biodiesel) displaces a prior land-use (e.g., forest), thereby generating possible changes in the carbon stock of that land.

- Indirect land-use change (ILUC) occurs if pressure on agriculture – due to the displacement of a previous activity from the production of biomass feedstock – induces land-use changes in other locations. The displacement of current land-use to produce biofuels and other bio-based products can trigger direct land-use changes elsewhere.

Land-use change consequently leads to the shortage of food supply and reduction in biodiversity when more agricultural lands and biological habitats are used for growing energy crops. These foreseeable impacts must be taken into account to ensure ecological and social sustainability with expansion of global bio-energy production in particular and bio-refinery in general.

To overcome these challenges, various stakeholders need to play different roles in the industrialisation process of biorefinery systems. Governments interested in supporting biorefineries for environmental protection and energy security should make significant investments in R&D, supply chain, distribution infrastructure, and conversion capacity, while carefully regulating the implementation process to ensure food security and avoid land-use change.

6. Conclusion

Biorefineries are facilities that sustainably convert biomass into energy, chemicals, and materials. The main driving force for the establishment of biorefineries is the call for sustainable development to ensure energy security, mitigate climate change, and meet the endless demand of chemicals and materials. Mandates and policies in each country also push to promote the implementation of biorefineries. To date, the biorefinery industry is mainly in the pilot and demonstration stages. Considerable developmental work is underway, and new biorefinery concepts are expected to be commercially deployed by 2020. The deployment of new biorefinery concepts based largely on lignocellulosic feedstock will need to rely on the technical maturity of a range of processes to produce materials, chemicals, and energy. The mix of market and governmental support for green materials and chemicals and for bioenergy will be an important factor in determining the type and rate of deployment of biorefineries. To promote the implement of new biorefinery concepts, the important roles of various stakeholders, nongovernmental organisations, and governments in the industrialisation process of biorefineries are indispensable.

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