Biochemical Engineering Journal 116 (2016) 122–134

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Regular article

Design strategies for sustainable biorefineries

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ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 12 May 2016
Accepted 6 June 2016
Available online 7 June 2016

Keywords:
Biorefinery concept
Biorefinery design
Mass index of biorefineries

ABSTRACT

The biorefinery concept is considered as one of the research cornerstones in the last years and as the best option to transform the different biomass systems into value-added products. A review about different approaches related to the modelling and assessment of biorefineries is presented taking into account raw materials, technologies, processing routes, products, and technical, economic and environmental aspects. Methodologies for biorefineries design as conceptual design, optimization and early-stage approaches are studied. Three main concepts are analyzed for the conceptual design of biorefinery systems: hierarchy, sequencing and integration. Finally, the proposed strategy for biorefinery synthesis is applied briefly to two previously cases developed by the authors. A mass index as a new basic concept is applied for understanding the biorefinery efficiency in terms of processing biomass.

1. Introduction

Fuels become less abundant and uncertainties in oil prices and volatility are currently a reality. Due to this and future constraints on carbon dioxide emissions, many countries have set up policies to support bio-based alternatives. The integrated use of biomass and the conversion in useful products is associated with the biorefinery concept, which in general terms imply the conversion of biomass into a suite of products ranging from bulk products (e.g., bioenergy) up to specialty chemicals. This concept is analogous to today's petroleum refinery, which produces multiple fuels and chemicals from petroleum [1,2]. A biorefinery can take advantage of the different biomass constituents and intermediates and maximize the value derived from the feedstock [3]. In this respect, the most effective and efficient utilization of renewable biomass resources is through the development of an integrated biorefinery. Through this strategy, it can be achieved greater profitability and environmental sustainability.

Due to the novelty of the biorefinery concept in the industry, in the last years there have been proposed design methodologies such as conceptual design, optimization and the combination of these, in order to avoid mistakes when the biorefineries reach an industrial reality [4–6]. For example, until just a few years ago the analogous oil refineries incurred in high levels of pollution because of the step-by-step design. In the beginning, the refineries were designed just for obtaining small quantity of products with huge production of residues, not disposed in some cases. This tendency was practically supported by very soft regulations in residues emissions. Just in last decades, the refining lines are increased in terms of chemistry and design development and hundreds of products are obtained using the same old plants and production basis. Therefore, in general terms the design methodologies allow assessing the raw materials, technologies, products, processing routes through technical, economic, environmental and energy analysis to obtain the best configuration of a process. The formulation of biorefineries schemes includes the adoption of three concepts chained, hierarchy, sequence and integration.

Based on the descriptions presented previously, this paper aims to discuss the biorefinery concept and different biorefinery design strategies. Additionally, it is proposed one strategy for biorefinery synthesis and its application to two biorefinery cases reported in the literature. An index to understand the preliminary performance of the biorefinery is also discussed.

2. Biorefinery concept

A biorefinery is a network of facilities that integrates biomass conversion processes and equipment to produce biofuels, energy and chemicals from biomass. Many authors define the biorefinery as the analogy to current oil refineries, which produce multiple fuels and chemicals from petroleum [1,2,7]. When the biomass and crude oil are compared, characteristics as renewability, storage, substitutability, abundance and carbon neutral (zero emissions) are

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http://dx.doi.org/10.1016/j.bej.2016.06.009
1369-703X/

highlighted, generating remarkable differences between these raw materials.

Other main difference appear in the feedstock distributions and opportunities when biomass is fractionated into a family of products with different added value [7].

Two major elements make oil refineries and biorefineries different. The first is the raw material, because those used in biorefineries have not undergone the biodegradation of crude oil over millions of years (Biomass is organic matter derived from living, or recently living organisms) [8]. The second is the complexity after application of different existing and emerging technologies in order to obtain bioproducts integrally and simultaneously. Furthermore, a biorefinery involves assessing and using a wide range of technologies to separate biomass into its principal constituents (carbohydrates, protein, triglycerides, etc.), which can subsequently be transformed into added-value products. The palette of products from a biorefinery not only includes the products obtained in an oil refinery, but also products that cannot be obtained from crude oil (the best example is food products) [2,7].

There are several points of view for biorefining options, which lead to different definitions and positions. In this way, this section aims to describe in a brief but clear way the different perceptions about biorefinery concept presented in the literature.

According to the International Energy Agency (IEA) Bioenergy Task 42, a biorefinery is defined as “A sustainable processing of biomass into a spectrum of marketable products and energy” [1]. Huang et al. [9] defined biorefinery as processes that use bio-based resources such as agriculture or forest biomass to produce energy and a wide variety of chemicals and bio-based materials, similar to the modern petroleum refineries [7]. Industrial platform chemicals such as acetic acid, liquid fuels such as bioethanol and biodegradable plastics such as polyhydroxyalkanoates can be produced from wood and other lignocellulosic biomass. In these definitions it is clear that the number and type of products is one of the most important characteristics of the biorefinery. This opens a discussion if plants producing bioethanol or biodiesel in stand-alone cases can be considered as biorefineries. In a broad definition, biorefineries process all kinds of biomass (all organic residues, energy crops, and aquatic biomass) to obtain numerous products (fuels, chemicals, power and heat, materials, and food and feed). It is important to note that the maximum use of the raw materials and minimum production of residues (increasing the number of products, if possible) is a type of sustainability challenge addressed to any biorefinery. The extraction of essential oils with yields normally about 1–2% and 98–99% in biomass residues cannot be considered as biorefinery if this residual biomass is not used as maximum as possible to obtain other products or energy for the self demand.

Generally, a biorefinery approach involves multi-step processes in which the first step, following feedstock selection, typically involves the treatment of biomass. This step is conventionally referred as pretreatment. After this stage, the biomass components are subject to a combination of biological and/or chemical processes. The outputs from this step (specialty chemicals or reducing sugars) can be converted to chemical building blocks for further processing uses [10].

The biorefineries can produce energy in the form of heat or by producing biofuels at large volumes and lower sale prices, and molecules for fine chemistry, cosmetics or medicinal applications with low volumes and higher sale prices. Also, materials such as plastics and sources of human food and animal feed can be produced [11,12].

These products based on bioresources can be obtained in a single productive process (stand-alone). However, the integrated production of chemicals, materials, energy and food is probably a more efficient approach for the sustainable valorization of biomass resources in future bio-based economies [13–15]. Future biorefineries will be able to imitate also the energy efficiency of modern oil refining through heat integration and development of co-products. Heat that is released from some processes within the biorefinery and it can be used to meet the heat requirements for other processes in the system. The biorefinery concept attempts to apply the methods that have been applied to the refining of petroleum to biomass conversion. The main goals of the biorefineries are to maximize the value of the products obtained from the biomass, to reduce the dependency of many countries on the fossil fuels, to reduce the emission of greenhouse gases and to stimulate regional and rural development.

All these concepts are the basis for understanding what is really the purpose of the biorefinery. In some cases the idea is to use the residues mainly to avoid the pollution when efficient disposal is not suitable [16]. Other case can be when the main purpose of the biorefinery is the valorization of residues as alternative to an existing efficient disposal method [17]. Biorefineries can be also proposed to improve the global supply chain for different crops as for example coffee, palm or sugarcane cases (including the maximal use of the residues to obtain high added value products) [13,18]. A specific case can be biorefineries designed for specific type of products as for example the energy producing biorefineries [19].

3. Raw materials, technologies and products

3.1. *Biorefinery raw materials*

Depending on raw materials, technological processes and products, the biorefinery involves different platforms such as sugar (biochemical), syngas (thermochemical), biogas, or carbon-rich chains platforms. A biorefinery can incorporate processes from different platforms and combine different processing routes. Some biorefinery platforms are described as biorefinery based on lignocellulosic biomass or biorefinery based on crops that integrated cereals with residues as an alternative feedstocks generation [20].

Nevertheless, it is important to describe also the raw materials classification. A way to help understanding this topic is to know its source and how can this affect the overall performance of a biorefinery in terms of the feedstock generation. First generation feedstocks include edible crops (e.g. edible vegetables oils, cane, rice, wheat). First generation feedstocks (1G) face social, economic and environmental challenges because these are derived from food crops. Their use can lead to increase food prices and to create pressure on land use, which makes it unlikely to be completely sustainable. Second generation feedstocks (2G) can overcome the social, economic and environmental challenges without hampering to food cost and creating pressure on land use because they are non-edible, biodegradable and can grow on marginal land [21,22]. 2G feedstocks overcome the fuel vs. food dilemma (e.g. wood, wood waste, non-food crops, waste cooking oil, forestry residues, and biomass resources). However, the competition of 2G feedstocks with feed and in some cases with fertilizing directly in the field can exist. Third generation feedstocks (3G), are mainly microalgae and have some remarkable advantages such as being cultured at low-cost, high energy, eco-friendly and entirely renewable [21,23].

In order to describe the classification presented by some authors, Table 1 shows examples of some classifications of biorefinery feedstocks. It is important to note that CO_2 is known as fourth generation feedstock [24]. Non-edible crops as jatropha or karanja are also considered as fourth generation feedstocks [25]. However, these materials are just a specific group in the first generation feedstocks.