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The biorefinery concept: Using biomass instead of oil for producing energy and chemicals

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ABSTRACT

A great fraction of worldwide energy carriers and material products come from fossil fuel refinery. Because of the on-going price increase of fossil resources, their uncertain availability, and their environmental concerns, the feasibility of oil exploitation is predicted to decrease in the near future. Therefore, alternative solutions able to mitigate climate change and reduce the consumption of fossil fuels should be promoted. The replacement of oil with biomass as raw material for fuel and chemical production is an interesting option and is the driving force for the development of biorefinery complexes. In biorefinery, almost all the types of biomass feedstocks can be converted to different classes of biofuels and biochemicals through jointly applied conversion technologies. This paper provides a description of the emerging biorefinery concept, in comparison with the current oil refinery. The focus is on the state of the art in biofuel and biochemical production, as well as discussion of the most important biomass feedstocks, conversion technologies and final products. Through the integration of green chemistry into biorefineries, and the use of low environmental impact technologies, future sustainable production chains of biofuels and high value chemicals from biomass can be established. The aim of this bio-industry is to be competitive in the market and lead to the progressive replacement of oil refinery products.

1. Background and introduction

Our strong dependence on fossil fuels comes from the intensive use and consumption of petroleum derivatives which, combined with diminishing petroleum resources, causes environmental and political concerns. There is clear scientific evidence that emissions of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), arising from fossil fuel combustion and land-use change as a result of human activities, are perturbing the Earth's climate [1]. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report highlighted that the world's growing population and per capita energy demand are leading to the rapid increase in greenhouse gas (GHG) emissions. In particular, over the past 10 years, transport has shown the highest rates of growth in GHG emissions in any sector [2].

The world's primary source of energy for the transport sector (and production of chemicals as well) is oil. World demand is approximately 84 million barrels a day and is projected to increase to about 116 million barrels a day by 2030, with transport accounting for some 60% of such a rising demand [3]. While the transport sector continues to expand in the US and Europe, growth in the emerging economies of India and China is predicted to be substantially greater, growing by at least 3% per year [4]. Concerning chemicals, their dependence on fossil resources is even stronger. The majority of chemical products are produced from oil refinery and almost 4% of oil is worldwide used for chemical and plastic production [5].

In order to simultaneously reduce the dependence on oil and mitigate climate change in transport and chemical sectors, alternative production chains are necessary. It is increasingly recognized that there is not a single solution to these problems and that combined actions are needed, including changes in behavior, changes in vehicle technologies, expansion of public transport and introduction of innovative fuels and technologies [6].

Recently, society began to recognize the opportunities offered by a future sustainable economy based on renewable sources and has been starting to finance R&D activities for its implementation. It is increasingly acknowledged globally that plant-based raw materials (i.e. biomass) have the potential to replace a large fraction of fossil resources as feedstocks for industrial productions, addressing both the energy and non-energy (i.e. chemicals and materials) sectors [7].

At national, regional and global levels there are three main drivers for using biomass in biorefinery for production of bioenergy, biofuels and biochemicals. These are climate change, energy security and rural development. The political motivation to support renewable sources of energy and chemicals arises from each

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individual driver or combinations. Policies designed to target one driver can be detrimental to another. For example, policies aimed at ensuring energy security may result in increased GHG emissions where local coal reserves are preferentially exploited at the expense of imported oil or gas. In addition, electricity and heat can be provided by a variety of renewable alternatives (wind, sun, water, biomass and so on), while biomass is very likely to be the only viable alternative to fossil resources for production of transportation fuels and chemicals, since it is the only C-rich material source available on the Earth, besides fossils. As a consequence, the sustainable biomass production is a crucial issue, especially concerning a possible fertile land competition with food and feed industries.

This paper investigates the possibilities to use biomass feedstocks as raw materials in biorefinery. Firstly, an overview of the current status in biofuel production is provided and then the emerging biorefinery concept is described. The latter is done through an overview of the most promising biomass feedstocks, technological processes and final products. The current oil refinery industry is taken as benchmark throughout the paper. Finally, after reviewing the strategic role played by green chemistry in establishing sustainable conversion technologies, some guidelines for future biorefinery complexes are proposed.

2. State of the art in biofuel production

Currently, transportation fuels based on biomass (i.e. biofuels) are identified as 1st and 2nd generation biofuels. First generation biofuels usually refer to biofuels produced from raw materials in competition with food and feed industries. Because of this competition, these biofuels give rise to ethical, political and environmental concerns. In order to overcome these issues, production of second generation biofuels (i.e. from raw materials based on waste, residues or non-food crop biomass) gained an increasing worldwide interest in the last few years as a possible "greener" alternative to fossil fuels and conventional biofuels. As a development of 2nd generation biofuel production, the use of biomass in biorefinery complexes is expected to ensure additional environmental benefits and implement national energy security, thanks to the coproduction of both bioenergy and high value chemicals.

2.1. First generation biofuels

First generation biofuels are produced from sugar, starch, vegetable oil or animal fats using conventional technologies. The basic feedstocks are often seeds and grains such as wheat, corn and rapeseed. The most common first generation biofuels are bioethanol, biodiesel and starch-derived biogas, but also straight vegetable oils, biomethanol and bioethers may be included in this category.

Bioethanol is recovered from biomass feedstocks such as sugarcane, sugar beet and starch crops (mainly corn and wheat). In 2006, total world production reached 51.3 billion litres. USA is currently the largest producer of bioethanol with a production of 19.8 billion litres per year, with corn as primary feedstock. Sugarcane is used as primary feedstock in Brazil, currently the world's second largest producer (17.8 billion litres per year). The European Union produces 3.44 billion litres of bioethanol, mainly from sugar beet and starch crops [8].

Biodiesel is produced from oil based crops such as rapeseed, sunflower, soybean but also from palm oil and waste edible oils. World biodiesel production surpassed 6 billion litres in 2006. Germany led biodiesel production in 2006, producing 2.5 billion litres mainly from rapeseed and sunflower. The USA are the second largest producer with 0.86 billion litres, but other countries (France, Italy, Austria) are increasing their biodiesel production [8].

Biogas is produced after anaerobic digestion of mixtures of corn derived starch, manure, organic waste and grasses. However, when biogas is mainly derived from waste and residues can be categorized as 2nd generation biofuel, because its feedstock is not in competition with the food and feed industry. The production of biogas is common in most world countries, and in the last few years it has been strong implemented in countries with economic subsides for electricity generation from biogas (especially European countries). In some countries (such as Germany and Sweden), biogas is also used as transportation biofuel, after upgrading to biomethane. For instance, Sweden leads the world in automotive biogas production, with a total fleet of approximately 4500 vehicles with 45% of its fuel supplied by biomethane [9].

The main advantages of first generation biofuels are due to the high sugar or oil content of the raw materials and their easy conversion into biofuel. Many biofuel production chains have been analysed by means of Life Cycle Assessment (LCA) in order to point out their environmental performances [10–12]. With the exception of a few studies, most LCAs have found a net reduction in global warming emissions and fossil energy consumption when the most common transportation biofuels (bioethanol and biodiesel) are used to replace conventional diesel and gasoline [13–15]. Several LCA studies have also evaluated life cycle impacts under other environmental aspects, including local air pollution, acidification, eutrophication, ozone depletion, land use, etc. These environmental burdens are much more affected by site specific assumptions than GHG and energy balances, showing that it is not that easy to draw simplified conclusions. Studies that have examined these other environmental issues have concluded that most, but not all, biofuels substituting fossil fuels lead to increased negative impacts [16,17].

In addition, 1st generation biofuels are in competition with food and feed industries for the use of biomass and agricultural land, giving rise to ethical implications: as prices for fossil fuels increase, a larger proportion of cereals or agricultural land will be dedicated to biofuel production instead of using it to produce food.

In conclusion, first generation biofuels currently produced from sugars, starches and vegetable oils cause several concerns: these productions compete with food for their feedstock and fertile land, their potential availability is limited by soil fertility and per hectare yields and the effective savings of CO_2 emissions and fossil energy consumption are limited by the high energy input required for crop cultivation and conversion [18,19]. These limitations are expected to be partially overcome by developing the so-called 2nd generation biofuels [20].

2.2. Second generation biofuels

Second generation biofuels are produced from a variety of non-food crops. These include the utilization of lignocellulosic materials, such as residues from agriculture, forestry and industry and dedicated lignocellulosic crops. In the scientific literature, the term 2nd generation shows wide variation in usage and can variably refer to feedstocks (e.g. lignocellulosic material), conversion routes (e.g. thermochemical, flash pyrolysis, enzymatic, etc.) and end products (e.g. gas or synthetic liquid biofuels).

Contrarily to first generation biofuels, where the utilized fraction (grains and seeds), represents only a small portion of the above-ground biomass, second generation biofuels can rely on the whole plant for bioenergy production. In fact, rapeseed grain yield is 3.4 t/ha but the oil content of the grain is only 40%, thus the 'effective' yield is reduced to 1.35 t/ha [21].

Second generation biofuels (e.g. Fisher Tropsch (FT)-diesel from biomass and bioethanol from lignocellulosic feedstock) promise advantages over 1st generation biofuels in terms of land-use efficiency and environmental performance, according to most of the