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High-value low-volume bioproducts coupled to bioenergies with potential to enhance business development of sustainable biorefineries

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ABSTRACT

Economically feasible production of conventional bioenergies such as biofuels, biopower and bioheat is a challenge in biorefineries because they have to compete with inexpensive fossil fuel energies while external production costs are rarely included into the present-day policies. Biomass consists of unique complex chemical structures that cannot be easily artificially synthesized and may be beneficially employed in various practical applications. Therefore, strategies relying on complete biomass disintegration through combustion, gasification or fermentation only to simple usable bioenergies do not lead to optimal utilization of biomass feedstock. Instead, cascading approaches are required in order to maximize biomass valorization. Consequently, high-value low-volume bioproducts coupled to bioenergies with potential to improve economic viability of biorefineries and biomass resource utilization are urgently required. Integrated production of bioenergies and bioproducts may be achieved by coupling existing biofuel plants with new bioindustries, by retrofitting existing bioindustries with new bioenergy facilities or by erecting completely new integrated facilities.

The current paper reviews literature and provides systematized insights into various high-value low-volume bioproducts coupled to bioenergies in biorefinery contexts. It analyses potential benefits of a range of such bioproducts and gives comments on associated business development. The review thus creates foundations for more thoughtful design procedures of economically feasible sustainable biorefineries that could meet technical and market requirements and improve cascading biomass utilization. Owing to insufficient technology readiness the study also aims at improved understanding of major technological gaps limiting expanded economically viable utilization of high-value bioproducts through biorefineries. It is emphasized that the major advantage of biorefineries is their suitability for maximizing valorization of structural and energetic potentials lying in biomass. The study suggests that new business models introducing high-value bioproducts to biorefineries are essential for achieving economic viability of industries within bioeconomy.

1. Introduction

Economically viable production of conventional bioenergies such as biofuels, biopower and bioheat from biomass is a challenge because of competition with relatively cheap fossil fuel energies. Since external production costs are rarely included in present-day policies bioenergies require business development enhancement. Biomass is highly diverse and consists of unique complex chemical structures that may be beneficially employed in various practical applications with little competition from fossil fuels. Therefore, strategies relying on biomass disintegration through combustion, gasification or fermentation only to simple usable forms of bioenergies do not lead to optimal utilization of biomass resources. Instead, cascading approaches are required in order to maximize benefits from biomass utilization in the entire value chain. Therefore, research efforts are directed at identifying solutions that could improve economics and resource use efficiency of biomass.

Abbreviations: 3-HPA, 3-hydroxypropionic acid; AD, anaerobic digestion; AHA, α-hydroxy acid; AX, arabinoxylans; BM, biomethane; BS, biosyngas; CAGR, compounded annual growth rate; CHP, combined heat and power; CMF, 5-chloromethyl furfural; DHA, docosahexanoid acid; DME, dimethyl ether; EA, ethyl acetate; EPA, eicosapentanoic acid; FA, ferulic acid; FDCA, 2,5-furandicarboxylic acid; FEE, furfuryl ethyl ether; F-T, Fischer-Tropsch; GABA, γ-aminobutyric acid; GHG, greenhouse gas; GVL, γ-valerolactone; HMF, 5-hydroxymethylfurfural; HTC, hydrothermal carbonization; IEA, International Energy Agency; LCA, Life Cycle Assessment; MEG, mono-ethyleneglycol; MFC, microfibrillar cellulose; MMA, methyl metacrylate; ML, methyl levulinate; MSW, municipal solid waste; NREL, National Renewable Energy Laboratory; PBS, polybutylene succinate; PE, polyethylene; PEF, polyethylene furanoate; PET, polyethylene terephthalate; PGA, polyglycolic acid; PHA, polyhydroxyalkanoate; PHB, poly-3-hydroxybutyrate; PLA, polyactic acid; PP, polypropylene; PPC, polypropylene carbonate; PTT, polytrimethylene terephthalate; PUFA, polyunsaturated fatty acid; PVC, polyvinyl chloride; R-PC, R-phycocyanin; R-PE, R-phycoerythrin; THF, tetrahydrofuran

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Potentially, coupling of conventional bioenergies and high-value low-volume bioproducts within biorefinery contexts could successfully address this challenge and enhance bioenergy related business development [1].

Biorefineries are emerging industrial systems that aim at sustainable and efficient utilization of biomass, valorize potentials lying in biomass resource and deliver multiple useful bioenergies and bioproducts. This understanding of the role of biorefineries in the economy is consistent with recent definitions provided by the leading energy organizations such as National Renewable Energy Laboratory (NREL): "A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power and (organic) chemicals from biomass" [2] and International Energy Agency (IEA): "Biorefinery is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)" [3]. Biorefineries are therefore more complex than conventional petroleum refineries that mainly fractionate oil into marketable transportation fuels while petroleum products are often obtained in separate facilities. Biorefineries will integrate several present-day industries, e.g. fuel, chemical and power, but will use biomass as a specific renewable feedstock. Their major advantage is that they are suitable for maximizing valorization of structural and energetic potentials lying in biomass. Biorefineries will be thus biofactories, a sort of multi-product bioconglomerates that will separate and convert biomass into a range of useful bioenergies and bioproducts, Fig. 1.

Biorefinery facilities deliver bioenergies and bioproducts. Bioenergies include low-value, but high-volume biofuels such as biodiesel, bioethanol or biogas as well as bioelectricity and process bioheat. Bioproducts are preferably high-value, but obtained in low-volumes and include biopharmaceuticals, biocosmetics, bionutrients, biochemicals, biofertilizers, and biomaterials. The high-value bioproducts are intended to increase profitability of biorefineries while the high-volume biofuels, biopower and bioheat generated in-situ lower energy costs for internal use and provide additional revenues.

Bioproducts that may be derived from biomass mainly depend on feedstock characteristics and employed processing routes. Especially high-value bioproducts attract commercial attention because with innovative technologies some of them can be obtained at a reasonable cost thus ensuring a meaningful profit margin. High-value bioproducts cannot be obtained in high-volumes from raw biomass because either they appear in low concentrations in biomass or they are obtained via sophisticated conversion routes with remarkable amounts of by-products. Bioproducts separations and biomass-to-bioproduct conversions are also energy and material intensive which increases production costs. The market value of bioproducts often depends not only on production costs but also on market conditions including competition from fossil fuel derived products, supply and demand relations, suitability for certain specific applications, etc. Bioproducts from biorefineries must suit the intended market and if the market evolves alternative bioproducts need to be available in order to follow market trends. Bioproducts with the highest commercial potential need to address market niches, be obtained at a reasonable cost and due to complex specific chemical structures avoid competition with fossil fuel derived products [4].

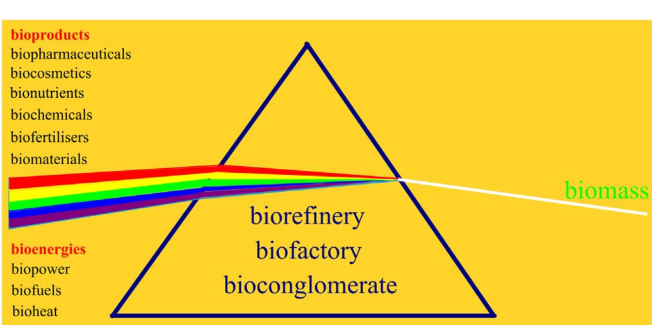

Fig. 1. Biorefinery (or biofactory or bioconglomerate) separating and converting biomass into a range of useful bioenergies and bioproducts.

Fig. 2 schematically presents values and volumes for various bioenergies and bioproducts that may be obtained from raw biomass in biorefineries. It is seen that especially some of biopharmaceuticals, biocosmetics and bionutrients may achieve high values but at the same time they can be produced only in relatively low volumes. Therefore, the valorization of biomass resource by conversions into a range of product with maximal total value with a good business model would improve economic feasibility of biorefineries.

The most promising high-value bioproducts combine large market volumes with medium to preferably high selling prices. With access to a versatile range of commercially attractive bioproducts biorefineries will be capable of conquering several markets and displacing many of current fossil fuel based industries. However, biorefineries are very specific facilities and their performance to high extent depends on adequate integration with the entire value chain including economic, environmental and social dimensions [5]. Specific nature of biomass necessitates the exploration of numerous aspects, including the selection of biomass harvesting sites, feedstock type, processing routes, targeted bioproducts, and market conditions [6]. It is likely that many future biorefineries will be unique in terms of high-value bioproducts they separate or synthesize from biomass. In contrast to biofuels high-value low-volume bioproducts can be economically transported over longer distances to be sold in new distant markets that are still unsaturated and could accept higher prices. However, biomass feedstock due to low energy density and high water content must be always available locally in sufficient quantities in order to minimize production costs. It is important that very cheap feedstocks are applied such as residues and wastes from agriculture or food/feed industry while agricultural and forest biomass is cultivated in a way that also ensures sufficiently low prices.

Global biomass consists mainly of carbohydrates (75%) such as cellulose, starch, chitin and sucrose as well as lignin (20%). Only about 4% of biomass is currently exploited commercially. Therefore, biorefineries should primarily aim at expanded commercial utilization of carbohydrates. Fossilized oil comprises mostly alkanes while biomass comprises e.g. pentoses, hexoses and naturally polymerized aromatics. Therefore, the logical strategy is not to break these sophisticated biomolecules and synthesize new ones because it would have to be energy and emission intensive. Instead, biorefineries should apply cascading approaches and separate naturally synthesized high-value biocompounds available in biomass while the residues should be further valorized to bioenergies and new value-added bioproducts and finally wastes should be processed to enable full reintegration with the environment. All these approaches require new advanced technological solutions and attractive business models before economically sound biorefineries can be created.

This review study has been undertaken in order to systematize knowledge on high-value low-volume bioproducts coupled to bioenergies generated in biorefineries from biomass. The study aims at improving economic viability of biorefineries and resource use efficiency by employing cascading approaches for biomass separation and conversion. It discusses (i) bioresources particularly suitable for high-value bioproducts generation, (ii) high-value low-volume bioproducts broken into several categories, (iii) business development of biorefineries in the context of high-value low-volume bioproducts, and finally (iv) illustrative realistic case studies of biorefineries employing high-value bioproducts coupled to bioenergies.

2. Bioresources for generating high-value bioproducts

In order to develop economically viable biorefineries it is imperative to exploit biomass to the maximum possible extent in a cascading