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Review

Chemicals from biomass – managing greenhouse gas emissions in biorefinery production chains – a review

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ABSTRACT

Growing concerns over the availability and cost of extracting fossil fuel resources have increased interest in renewable resources. Therefore, interest in producing numerous needed chemicals from renewable biomass resources has increased. The focus of this comprehensive review is on managing greenhouse gas emissions (GHG) in biorefinery production chains. To highlight the results of the content analysis an attempt is made to summarize the findings in a climate impact management matrix. In particular, three topics from the matrix are put forward: (1) uncertainties in assessing GHG emissions of feedstock cultivation, harvesting and logistics; (2) found GHG emissions in biorefinery chains; and (3) a short comparative analysis of two potential technologies to improve the GHG and carbon balance of biorefinery operations. In addition, benefits of lignocellulosic biomass, residuals, organic waste and algae are highlighted, sustainability issues of the field are discussed and research gaps are identified. Uncertainties in assessing the sustainability of biofuels supply chains support a more diversified renewable resource base and production of multiple chemicals in biorefinery chains.

1. Introduction

Growing concerns over the availability and cost of extracting fossil fuel resources have increased interest in renewable resources. On the other hand, reducing anthropogenic greenhouse gas (GHG) emissions is increasingly proposed as one of the key components in achieving global sustainable development goals. Therefore, interest in producing numerous needed chemicals from renewable biomass resources has increased. Renewable biomass resources can be converted to chemicals, and have the potential to replace fossil crude oil as a carbon resource. Production chains starting from renewable biomass resources are considered as 'short-cycle carbon systems' to be more sustainable than 'long-cycle carbon systems' using a fossil fuel resource base. Currently, most chemicals produced from biomass are identified as first and second generation biofuels: bioethanol (largest volumes, 80 billion liters in 2012), biodiesel and biogas (www.ethanolproducer.com). Since biomass is the only renewable carbon resource that could replace fossil ones, the availability and sustainability of these resources is of crucial importance. Biofuels are politically promoted (RED, 2009), and different types of sustainability concerns have arisen including the actual climate impact of biofuels and how extensively they can be utilized without causing significant and irreversible harmful environmental and social impacts. Production of various chemicals from biomass instead of fossil resources requires a paradigm change. The basic question in replacing existing petroleum refinery based production patterns of chemicals with biorefinery processes is the overall sustainability. This change can be studied with impact assessment covering all three pillars of sustainability: economic, social and environmental. Several sets of sustainability indicators and methodologies for estimating the impacts have been proposed (Sacramento-Rivero, 2012). The theoretical sustainability impact assessment framework for a biorefinery chain can be defined on a global, on a regional or on a production site level. On the product or process level, Life Cycle Assessment (LCA) is a methodological tool widely used for estimating and assessing impacts of production systems through their whole life cycle (ISO 2006:14040, ISO 2006:14044). The life cycle of a single site biorefinery consists of feedstock cultivation, harvesting, transportation, intermediate storage, pretreatment, biorefinery operations, product storage, packaging, distribution to customers, use of products, possible recycling and final disposal. The attributional LCA (ALCA), on a cradle to gate basis, reflects the biorefinery production system as it is. Impact allocation cannot be avoided in a biorefinery complex with several product streams. Energy or economic allocation is widely used in published LCAs

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and several options for handling uncertainties are proposed (Finnveden et al., 2009). Striving for sustainable use of resources requires reducing environmental impacts. Especially the net leakage of greenhouse gas emissions needs a serious assessment even when renewable biomass resources are replacing more pollutant fossil fuel derived products. The focus of this paper is on managing GHG emissions in biorefinery chains producing chemicals from biomass. The climate impacts discussed and analyzed here are expressed as greenhouse gas emissions (GHG) attributable to specific chemicals found in the literature. Other related environmental impacts like eutrophication are mostly excluded here. The overall sustainability assessment of biorefinery chains requires, in addition to product level analysis, global and regional analysis that is basically out of the scope of this paper. This review follows, focusing on GHG emissions, the production chain and climate impact matrix described in Section 2. Section 3 covers feedstock issues of cultivation, harvesting, collection, transport and storage, and highlights the uncertainties related to the assessment of GHG emissions attributed to the feedstock supply chain. Section 4 summarizes biorefinery concepts and highlights the GHG emissions of chemicals produced in biorefinery chains. In Section 5 two technologies to improve the GHG balance of biorefinery operations (pyrolysis and hydrothermal liquefaction) are shortly described and compared. Section 6 includes a short discussion including identified gaps in research. Conclusions are presented in Section 7. Abbreviations CO_2 and N_2O are used for carbon dioxide and nitrous oxide.

2. Research methodology

The aim of this review is to summarize the existing research by identifying patterns, themes and issues, and to determine the conceptual content of the field. The search was conducted using databases available from major publishers. The scope covers a total of 340 papers with emphasis on the 238 published in 2011–2013. A short patent search was made for the potential future large scale technologies that were identified in the course of the research.

2.1. Descriptive analysis and category selection

The production chain (Fig. 1) was used for the category selection. A robust classification of publications according to their place in the production chain, supplemented with specific issues of sustainability/LCA, resulted in the topical distribution of publications shown in Fig. 2 and Fig. 3.

2.2. Material evaluation

The papers studied were analyzed for the identification of relevant issues and interpretations of results. Here an attempt is made to summarize the findings including the system boundary setting in a climate impact management matrix (Fig. 1) elaborated further in the next sections of this paper.

In particular, three topics from the matrix are put forward: (1) uncertainties in assessing GHG emissions of feedstock cultivation, harvesting and logistics; (2) the found GHG emissions of chemicals produced in biorefinery chains; and (3) a comparative analysis of two potential technologies to improve the GHG and carbon balance of biorefinery operations.

3. Feedstock cultivation, harvesting, collection, transport and storage

Renewable feedstock is seldom without GHG emissions when direct and indirect emissions in the supply chain are taken into account. It is notable that lignocellulosic (other than agricultural crops), multiple feedstock (includes at least one lignocellulosic resource) and algae dominate recent research, although feedstock sustainability or LCA studies concentrate on cultivated crops (Fig. 3). When focusing on GHG emissions, an LCA analysis of feedstock supply chain reveals the possibilities to reduce GHG emissions. Biomass feedstock is not uniform in GHG emissions as e.g. a single crude oil field. Therefore, uncertainties in assessing feedstock GHG emissions have raised concerns on the climate impact of bio-based chemicals. Another important issue is how extensively can biomass be utilized without causing significant and

Cradle-to-gate Climate Impact Matrix	Feedstock cultivation	Feedstock harvesting and collection	Feedstock transport and storage	Biorefinery operations	Total product climate impact
Impact Assessment LCA	• Energy use • Fertilizer and pesticide use • Direct land use change	• Energy use • Machninery use	• Energy use • Storage losses	• All process emissions inluding use of chemicals and energy carriers	**Summary emissions of greenhouse gases (GHG)**
Reduction of GHG emissions	• Switch to residues, waste, lignocellulosic feedstocks and algae • Good management practices	• Spatial and temporal optimization • Minimization of auxliary energy use • Optimal machinery use	• Optimization of logistics • Less emitting transport equipment	• Technology development • Process intensification • Energy optimization • Feedstock and product optimization	• Optimization of whole biorefinery value chain • Elimination / reduction of uncertainties in the value chain
Outside Boundary System	• Indirect land use change • Resource depletion • Competition with food and feed production	• Emission of machinery production	• Emission of transport equipment & storage infrastucture production	• Emission from biorefinery plant infrastucture production	• Changes in related energy, feedstock and product markets
Fossil Reference System	Crude oil exploration	Upstream crude oil production	Crude oil transport and storage	Petroleum refinery operations	Internationally accepted reference values

Fig. 1. A matrix for managing greenhouse gas emissions in a biorefinery production chain.