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Environmental impacts of producing bioethanol and biobased lactic acid from standalone and integrated biorefineries using a consequential and an attributional life cycle assessment approach

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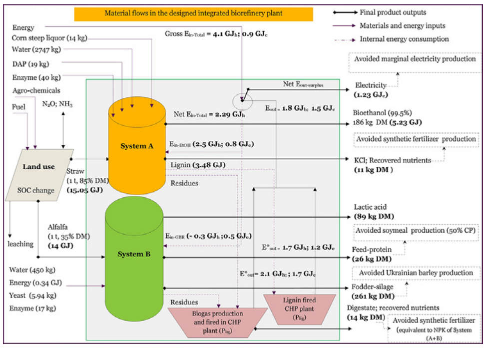
HIGHLIGHTS

- Environmental LCA was carried out for biobased products, both fuel and non-fuel.
- Biobased products produced from standalone and integrated biorefinery plants were evaluated.
- The evaluation included both consequential and attributional (economic allocation) approaches.
- The production of biomass and enzyme were the major environmental hotspots.
- System integration had better environmental performance and arrived at similar conclusions regardless of the approaches used.

GRAPHICAL ABSTRACT



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ABSTRACT

This study evaluates the environmental impacts of biorefinery products using consequential (CLCA) and attributional (ALCA) life cycle assessment (LCA) approaches. Within ALCA, economic allocation method was used to distribute impacts among the main products and the coproducts, whereas within the CLCA system expansion was adopted to avoid allocation. The study seeks to answer the questions (i) what is the environmental impacts of process integration?, and (ii) do CLCA and ALCA lead to different conclusions when applied to biorefinery?. Three biorefinery systems were evaluated and compared: a standalone system producing bioethanol from winter wheat-straw (system A), a standalone system producing biobased lactic acid from alfalfa (system B), and an integrated biorefinery system (system C) combining the two standalone systems and producing both bioethanol and lactic acid. The synergy of the integration was the exchange of useful energy necessary for biomass processing in the two standalone systems. The systems were compared against a common reference flow: "1 MJ_{EtOH} + 1 kg_{LA}", which was set on the basis of products delivered by the system C. Function of the reference flow was to provide service of both fuel (bioethanol) at 99.9% concentration (wt. basis) and biochemical (biobased lactic acid) in food industries at 90% purity; both products delivered at biorefinery gate. The environmental impacts of interest were global warming potential (GWP_{100}), eutrophication potential (EP), non-renewable energy (NRE) use and the agricultural land occupation (ALO). Regardless of the LCA approach adopted, system C performed

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better in most of the impact categories than both standalone systems. The process wise contribution to the obtained environmental impacts also showed similar impact pattern in both approaches. The study also highlighted that the recirculation of intermediate materials, e.g. C_5 sugar to boost bioethanol yield and that the use of residual streams in the energy conversion were beneficial for optimizing the system performance.

1. Introduction

The increasing demand for biomass to biofuels has spurred the food vs fuels debates and has led to investigate the impacts of devoting croplands for biofuels production (Lange, 2007; Marris, 2006). Studies on 1st generation biofuel production (based on food crops) have stressed on their poor environmental performance (Gressel, 2008; Mosier et al., 2005; Sims et al., 2010). Meanwhile, the environmental life cycle impacts of the 2nd generation bioethanol production were also largely determined by the types of biomasses and the system boundaries considered for the assessment (Luo et al., 2010). Example, switchgrass, sugarcane and sugar beet showed varied environmental performance in the biofuel conversion pathway (Luo et al., 2010; Muñoz et al., 2013). Furthermore, direct and indirect land use change (d/iLUC) impacts, as expected to be induced during the production of biofuels and biobased products are also extensively debated (Khanna et al., 2011; Templer and van der Wielen, 2011). Moreover, biorefinery technologies are bringing new types of biobased products (Cherubini, 2010) on a comparable functional basis to fossil based products (Mickwitz et al., 2011) and also aimed at addressing such environmental consequences by producing both fuel and food/feed commodities. Maximizing the values of biomass feedstocks by utilizing most of its components to produce both fuel and non-fuel products can be regarded as one of the sustainable solutions to manage the available biomasses to meet the future multi-fold demand of commodities (IEA, 2011; Parajuli et al., 2015).

Among the different biorefinery concepts, the green biorefinery (GBR) technology is seen as an alternative option for capitalizing the grassland biomass in Europe (Mandl, 2010; O'Keeffe et al., 2011). The GBR, until now, primarily aimed at producing protein in order to reduce the import dependency of livestocks feed (e.g. soy cake and soy meal) and also producing high value chemicals (e.g. lactic acid and lysine) (Kamm et al., 2009). Green protein is important in the livestock sector, while biobased lactic acid is important for the food, pharmaceuticals and chemical industries (Ghaffar et al., 2014; Kamm et al., 2009; Kim and Moon, 2001; O'Keeffe et al., 2011; Panesar et al., 2007; Thomsen, 2004; Wee et al., 2006). The global market production of biobased lactic acid in 2013 was 300–400 kt (ktons) (Harmsen et al., 2014). The production is expected to reach 800 kt in 2020 (Dammer et al., 2013), driven by the demand of polylactic acid (Harmsen et al., 2014). In these contexts, biorefining of green biomasses is often seen as a sustainable path to deliver high value biobased products and also achieving many societal goals (IEA, 2011). Despite its technical viability are well described in many studies (Dale, 2003; Harmsen et al., 2014; Kamm et al., 2010; Kamm et al., 2009; O'Keeffe et al., 2011), environmental impacts of its products' value chains are limitedly studied (Parajuli et al., 2015).

Life cycle assessment (LCA) has been widely used as a tool for the assessment of environmental performance of different products and services (European Commission, 2015a). According to ISO (2006), the main phases of an LCA are (i) goal & scope definition: where the product or service to be assessed is defined, a functional basis for comparison is chosen, (ii) inventory analysis: where the details on the data used for the assessment are discussed, (iii) impact assessment: where the effects of the resource use and the generated emissions are quantified into a limited number of impact categories, and (iv) interpretation of the results: where results are reported in the most informative way, along with the opportunities to reduce the impact of the product(s) or service(s). Furthermore, whenever, a product system involves multiple products, choices on the approach to handle the co-products are unavoidably connected (Thomassen et al., 2008). With regard to the environmental evaluations of different biobased products, it is thus relevant to develop and apply standardized LCA methodologies that can cover the wide range of products delivered from a product system (European Commission, 2015b; ISO, 2006). This is generally carried out by using either; subdividing the multi-functional processes, system expansion and allocation (European Commission, 2010). In this context, attributional (ALCA) and consequential (CLCA) approaches were aimed to resolve the methodological debates over the allocation problems and also the choice of data (Thomassen et al., 2008). Within ALCA approach, allocation can be avoided by using system expansion to handle the co-products, but the co-product allocation is widely used (Thomassen et al., 2008). In general, if avoiding allocation is not possible, the ISO series (ISO, 2006) recommends using methods that reflects the physical relationship, such as mass and energy content or using other relevant variables to allocate, such as economic value of the products (Guinée et al., 2004). In the current study, economic allocation method was used, as is most frequently used (Crown and Carbon Trust, 2008). Within CLCA approach, avoiding allocation by system expansion is the only acknowledged way to deal with the co-products (Weidema, 2003). Moreover, it is also relevant to examine, whether the choice of any of the methods would end-up with different conclusions on the environmental ranking of any product system. Within such scope, comparative assessments using ALCA and CLCA approach were also practiced in various studies, e.g. as reported in Thomassen et al. (2008) and Sanchez et al. (2012).

This study aims at evaluating the environmental impacts of biorefinery products using a LCA method. Evaluations were made for two standalone biorefinery plants, separately producing bioethanol (system A) and biobased lactic acid (system B), and was compared with an integrated system (system C) producing the both stated products. The integrated system was termed in accordance to the definitions for “process integration” and “feedstock and product integration” (Stuart and El-Halwagi, 2012). The integration aimed to assess possible synergies between two different plants, so that they can be constructed at the same place to optimally utilize the resources and minimize the related burdens of logistics. Evaluation was carried out by using both ALCA and CLCA approach.

2. Materials and methods

2.1. Goal and scope

The goal of the current study is to evaluate and compare two standalone biorefinery systems with an integrated biorefinery plant, which combine the two standalone systems on the basis of the possible synergy between them. The study also examined whether CLCA and ALCA approach considered for the environmental evaluation of biorefinery systems would arrive with same conclusions.

2.2. System boundaries, functional units and environmental impact categories

The evaluation covered the production and conversion of two different biomasses to produce two biobased products in an integrated biorefinery system (system C). The assumed geographical boundary was Denmark. A comparative assessment was made between system