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Techno-environmental assessment of the green biorefinery concept: Combining process simulation and life cycle assessment at an early design stage

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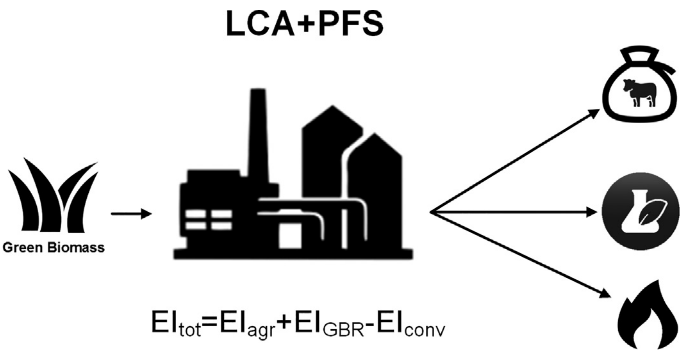
HIGHLIGHTS

- PFS + LCA combined to screen the environmental performance of different GBR setups.
- The GBR environmental profile is highly affected by the press-pulp utilization.
- Environmental savings to conventional products depends on the GBR configuration.
- Configurations prioritizing protein extraction efficiency lead to highest savings.
- Local protein-rich feed production can lead to reductions of climate change impacts.

GRAPHICAL ABSTRACT



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ABSTRACT

The Green biorefinery (GBR) is a biorefinery concept that converts fresh biomass into value-added products. The present study combines a Process Flowsheet Simulation (PFS) and Life Cycle Assessment (LCA) to evaluate the technical and environmental performance of different GBR configurations and the cascading utilization of the GBR output. The GBR configurations considered in this study, test alternatives in the three main steps of green-biorefining: fractionation, precipitation, and protein separation. The different cascade utilization alternatives analyse different options for press-pulp utilization, and the LCA results show that the environmental profile of the GBR is highly affected by the utilization of the press-pulp and thus by the choice of conventional product replaced by the press-pulp. Furthermore, scenario analysis of different GBR configurations shows that higher benefits can be achieved by increasing product yields rather than lowering energy consumption. Green biorefining is shown to be an interesting biorefining concept, especially in a Danish context. Biorefining of green biomass is technically feasible and can bring environmental savings, when compared to conventional production methods. However, the savings will be determined by the processing involved in each conversion stage and on the cascade utilization of the different platform products.

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1. Introduction

In recent years, the utilization of biomass for the production of feed, fuel and fibers has been suggested as one of the most promising solutions to fight climate change and reduce our dependence on petroleum derivatives. Several strategies have been proposed for the upgrade of biomass feedstock into a large array of products. Initial research, focusing on the utilization of food crops for the production of biofuels showed the technology to be technically and economically feasible (Worldwatch Institute, 2006). However, concerns were quickly raised regarding competition for land (i.e. the "food vs fuel dilemma") (OECD, 2008) and environmental savings, in comparison to traditional fossil fuels, were shown to be small (if any) when land use changes were included in the environmental sustainability assessment (Fargione et al., 2008; Searchinger et al., 2008). Since then, interests have shifted to the utilization of non-edible crops and crop residues in biorefineries: the so-called second-generation feedstocks. The goal of a biorefinery is to utilize all biomass fractions in order to maximize the product yield per biomass input, in the same way conventional refineries have been optimized to produce a multitude of products by exploiting all the crude oil components.

Biorefineries can be classified depending on the type of biomass feedstock they use (Bell et al., 2014; Cherubini et al., 2009; Kamm, 2013). The most prominent biorefinery concepts are: "yellow" biorefineries that utilize "dry" lignocellulosic materials; "green" biorefineries that utilize nature's "wet" grasses and immature crops; "blue" biorefineries that use algae; and "grey" biorefineries that utilize food waste.

Of particular interest, especially for the Danish context, is the green biorefinery. The green biorefinery aims at exploiting certain biomass components, which are generally lost during the maturation or drying of the biomass. Those components are generally water-soluble compounds, which become hard to fractionate when water is removed from the plant cell. The green biorefinery generally fractionates a "wet" biomass into a liquid stream and a solid stream (Xiu and Shahbazi, 2015). From these two streams, different cascading products can be generated depending on the processes involved (Kromus et al., 2006).

Three aspects make the green biorefinery concept interesting for the Danish scenario, as it can:

1) Decrease import dependency on protein-rich feed for the extensive Danish livestock sector.
2) Stimulate the local agricultural sector.
3) Increase synergies between different agricultural sectors (i.e. pig and poultry husbandry, dairy production and crop farming).

Due to intensive livestock production in Denmark, approximately 36 million tons of feed-products were consumed in 2015. While roughage and cereals are almost entirely produced in Denmark, approximately 80% of the protein-rich feed is imported (Bosselmann et al., 2015), and local production consists mainly of rape cakes and other by-products from the food industry. Soya by-product imports (cakes) account for approximately 50% of the total protein-rich feed consumption and 62% of the total import of protein-rich feed. Soya is imported mainly from South America directly, or re-exported from other EU countries, and a minor import comes from USA (Termansen et al., 2016). Fig. SI-5 in the Supporting Information (SI) shows the soy-based feed import to Demark in 2015. Due to socio-political concerns and environmental problems connected to soy production, as well as the added benefit of not paying for soya imports (Cong and Termansen, 2016), there is an active interest to reduce import dependency and look for local alternative protein sources (Hörtenhuber et al., 2011; Lehuger et al., 2009). In the SI, Table SI-17 presents the consumption of the most important protein-rich feed in Demark between 2010 and 2015.

The second aspect is the intensification of Danish agriculture. Cereals occupy a majority of Danish farmland and knowhow on cereal cultivation is estimated to be already at its maximum. Thus, limited improvement can be achieved in countries where intensive farming is already practiced. Annual crops such as cereals cannot use a significant part of the solar radiation during the growing season for photosynthesis and biomass production. Cereal crops mature from mid-July, are harvested in August, are re-sown in September and green fields are not seen until the very end of the year (Termansen et al., 2016). Grasses on the contrary, are perennial crops that can utilize solar radiation available year-round, achieving higher DM yields on a yearly basis (Gylling et al., 2016). Having a permanent soil cover, not only allows for higher yields, but can also bring benefits by minimizing nutrient losses. Eriksen et al. (2014) compiled a catalogue of measures, which may be used to mitigate nitrogen leaching in Denmark. In this context, the conversion of land from cereals to permanent intensive grass has been suggested as a relevant mitigating measure. In addition to reductions of nitrogen leaching, the transition from annual crops to perennial crops is also expected to lead to an increase in the carbon stock in the soil, due to the larger root system, and it will also lead to a decrease in the pesticide use compared to cereals (Jørgensen and Lærke, 2016).

Finally, the green biorefinery concept could improve synergies between pig and poultry farmers, dairy farmers and crop producers, on the one hand developing alternative and local protein sources and on the other intensifying the use of arable land (Cong et al., 2017; Gylling et al., 2016).

Given the potential of GBR to bring benefits across sectors, several projects have focused on developing the technology. Despite the common basic technology, i.e. fractionation of a wet feedstock into a liquid and a solid fraction, different process configurations and different target products have been developed, see Table 1. Several techno-economical assessments have been published, suggesting that the GBR could be feasible and economically competitive (Kamm et al., 2016; O'Keeffe et al., 2012; Sinclair, 2009). However, until now, knowledge on the best configuration remains limited, due to limited penetration and implementation in the biorefinery market. Furthermore, few studies have looked at the environmental sustainability of the GBR system (Cong and Termansen, 2016; Corona et al., 2018; Parajuli et al., 2017a) and none have focused on finding the most sustainable GBR value-chain.

Therefore, the present study performs a techno-environmental assessment of different GBR configurations. In order to estimate the technical performance of different GBRs, at an early design stage, a Process Flowsheet Simulation (PFS) of different GBR configurations was developed. The PFS, based on experiments and production trials performed at a pilot plant in (Foulum, DK), estimates material and energy input, as well as quantity and quality of the products for each configuration. The PFS's results were used to populate the inventory of the LCA model, in order to screen the best configuration in terms of environmental performance, to identify hotspot and focus points for the technology developers within the conversion pathway. Finally, a sensitivity analysis was used to look at the effect of process optimization on the environmental performance of the GBR.

2. Materials and methods

2.1. Description of the green biorefinery

A GBR pathway can be described in five main steps:

1) Biomass cultivation
2) Fractionation
3) Precipitation
4) Protein separation
5) Downstream processing of the GBR output