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Original article

Environmental analysis of a lignocellulosic-based biorefinery producing bioethanol and high-added value chemicals

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ABSTRACT

Lignocellulosic-based biorefineries for co-production of bioethanol and high added-value products are continuously gaining research interest. In this study, life cycle assessment (LCA) was applied to evaluate the environmental impacts of bioethanol and biochemicals co-production from a *Phalaris aquatica* L.-based biorefinery located in Greece. This LCA approach assesses the greenhouse gas (GHG) emissions and energy efficiency, considering the lignocellulosic biomass production chain and its conversion steps in the biorefinery for bioethanol and succinic acid production. Three scenarios were developed to determine the environmental characteristics of the biorefinery accounting the plantation characteristics and its biomass yields. Based on the results, the favorable environmental characteristics of the examined biorefinery system were identified. The estimated GHG and energy intensity varied depending on the scenarios studied, thus highlighting regional biomass yields and the impacts of agricultural inputs. Additionally, the energy emissions were found to be the top contributor to the GHG emissions, related to the Greek electricity grid mix. The sensitivity analysis showed that the electricity network can affect the results, hence highlighting the importance of process energy supply. Consequently, it is evident that dedicated perennial herbaceous energy crop appears to be a promising biomass resource towards sustainable biorefineries systems, maximizing GHG emissions reduction.

Introduction

Considering the intensive utilization of fossil fuels, the depletion of petroleum resources and the increased greenhouse gas (GHG) emissions, renewable energy sources are being extensively investigated [4]. Biofuels are considered sustainable bio-based transportation fuels and key alternatives to fossil-based fuels [6]. 1st generation biofuels produced from energy crops raised significant barriers (e.g food-versus-fuels issues, land use change etc.) that could be overcome by 2nd generation biofuels originating by variant types of biomass. In particular, lignocellulosic biomass (e.g crop and paper residues, wood, solid wastes etc.) constitutes a potential sustainable resource for bio-based fuels [7].

Bioethanol production via lignocellulosic feedstock conversion under a biorefinery system appears to be promising in mitigating global climate change involving also the co-production of biochemicals [10]. Lignocellulosic biomass complex structure is mainly composed of cellulose, hemicellulose and lignin that can be converted to bioethanol via biochemical routes [20]. More specifically, in a biorefinery platform variant biochemical conversion technologies are combined producing bioethanol and a wide spectrum of high-added value products [5]. Nearly all the biological technologies for lignocellulosic materials conversion to bioethanol involve firstly a pretreatment step in order to remove contaminants and reduce moisture. Dilute acid pretreatment followed by enzymatic hydrolysis converts lignocellulosic biomass to fermentable sugars. The fermentation of hexoses and pentoses into bio-products follows which are afterwards purified by distillation and/or filtration [2]. The research in this field is extensive, as the feedstock availability and the related logistics influence the bioethanol technology applicability and effectiveness [29].

Due to the multi-functionality of lignocellulosic biorefineries, their environmental profile evaluation should be thoroughly examined in an attempt to point out sustainable bio-based fuels and products and ascertain optimal biofuel processes [21]. Life cycle assessment (LCA) constitutes a valuable methodology for the environmental impacts evaluation of biofuels and has been applied for bioethanol production technologies from different feedstocks [19,25,30,31]. Since GHG emissions reduction and energy security are the main driving forces for promoting biorefineries, several LCA studies have addressed GHG and energy balances of bioethanol from lignocellulosic sources and in some

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occasions other environmental burdens such as acidification, eutrophication are also quantified, though characterized as site-oriented [29].

Particularly, Karrlson et al. [19] assessed GHG performance and energy balance of ethanol co-production with biogas and electricity in a biorefinery using straw and forest residues. The processes consisted basically of a pre-treatment step followed by simultaneous hydrolysis and fermentation and anaerobic digestion. Ethanol produced from forest residues generally gave lower GHG emissions than straw-based ethanol, while enzymes used in the process and the reduction in soil organic carbon due to residues removal influenced the results.

Moreover, LCA was applied to assess the environmental impacts of an oil palm-based biorefinery concept for the co-production of cellulosic ethanol and phytochemicals. Based on a cradle-to-gate perspective the study considered the biomass cultivation and transportation to the biorefinery. After the biomass pretreatment simultaneous saccharification and fermentation followed while the last step included purification of ethanol by means of distillation. Due to the use of fossil fuels, pesticides etc. GHG emissions, acidification potential and human toxicity potential were the most significant environmental impact categories for the whole biorefinery, pinpointing major areas for improvements actions towards sustainable biofuels production [22].

The study of Pieragostini et al. [25] evaluated the environmental impacts of anhydrous ethanol production from corn crop, applying LCA methodology. After biomass production and transportation to the plant, all stages until anhydrous ethanol production were considered: milling, liquefaction, saccharification, distillation, dehydration and stillage treatment. The results demonstrated that the use of fertilizers and resources had the highest impacts in the categories of acidification/eutrophication and climate change. Regarding ethanol production process the supplied heat and burned natural gas contributed significantly to several impacts categories (eg. acidification/eutrophication, climate change etc.)

LCA was used to evaluate the GHG emissions and energy efficiency of bioethanol production from sweet sorghum stem, including biomass cultivation and transportation and then its conversion to bioethanol. The bioethanol conversion unit included feedstock smashing, yeast inoculation, continuous solid state fermentation and distillation, bioethanol purification and vinasse treatment. The bioethanol production showed positive energy efficiency, while human toxicity was identified as the most significant negative environmental impact, followed by eutrophication and acidification. The bioethanol conversion unit was the main contributor to fossil energy consumption because of large coal consumption for steam generation [30].

In another LCA study Silalertruksa et al. [27] evaluated the sustainability of a sugarcane biorefinery ethanol production. In the study the sugarcane cultivation and transportation was included followed by its milling for bagasse (used for energy generation) and mollases separation. Ethanol production from molasses involved yeast preparation, fermentation, distillation and dehydration. Three scenarios integrating the utilization of biomass resources in the sugar–electricity–ethanol production system were evaluated. The results showed that the biorefinery system of mechanized farming along with cane trash utilization for power generation yields the highest environmental benefits.

LCA was applied to identify the environmentally-friendly options for enhancing the sustainability of a "sugar-power-ethanol" production system. The biorefinery system includes sugarcane cultivation and harvesting, milling and by-product utilization for energy, fuels and fertilizers production. The outcomes showed that the mechanized farming (and green cane harvesting) with integrated utilization of biomass residues through the entire chain could decrease several environmental impacts (e.g climate change, acidification, photo-oxidant formation, particulate matter formation and fossil depletion) of products derived from sugarcane [28].

The LCAs for rice straw as an agricultural waste, napier grass as an energy crop, and short rotation eucalyptus spp., as bioethanol feedstocks in fallow paddy fields were evaluated by LCA. The LCAs of two schemes for on-site fermentation waste utilization were also employed as pellet fuel and molded pulp feedstocks. Due to higher biomass yields, planting napier grass and Eucalyptus spp. resulted in 47% and 28%, respectively, lower weight-based negative impacts compared to planting rice. Nevertheless, the development of fermentation waste utilization could be considered for a thorough evaluation of alternative crops as potential bioethanol feedstocks thus appropriate for regions requiring high-energy imports [3].

Even though GHG emissions reduction and positive energy balance are achieved in the life cycle of bioethanol from lignocellulosic feedstocks key methodological issues (e.g functional unit, system boundaries, co- and by-products, allocation etc.) for quantifying the releases in the environment have been acknowledged [29]. Therefore, variations in methodological issues in LCA approaches on lignocellulosic bioethanol limit their outcome direct comparison, leading to a wide range of results underlining the necessity for homogenous approaches among researchers [21]. Apart from the methodological assumptions ranges in LCA results can be even more enlarged accounting the complexity of the biorefineries systems due to variant biomass feedstocks combinations, conversion routes and end use-applications [5].

Among the various available lignocellulosic feedstocks the scientific community is exploring types with minimum GHG emissions from their cultivation, not competing with food markets thus addressing the issue of sustainability towards GHG balance in biofuels production chains.

Phalaris aquatica L. is a perennial herbaceous lignocellulosic plant native to the Mediterranean area, with high biomass yield potential, drought tolerance, low pesticides and fertilizer demands and annual or in many cases less frequent harvests [23,24]. It is cultivated in marginal farmlands and the biomass capacity ranges from 6.3 to 11 t/ha dry mass with no agrochemical inputs [24]. Like other perennial plants *Phalaris aquatica* L. has also the advantage of low establishment costs [29]. Recently the production of bioethanol and biochemicals via an integrated bioprocess involving the use of *Phalaris aquatica* L. as feedstock has been investigated [17,18]. Particularly, beyond the fermentative production of bioethanol the synthesis of succinic acid-a high value chemical by the fermentation of the pentose monomers, liberated from the pretreatment stage was pursued, along with internal energy coproduction contributing to the plant energy requirements. The novelty of this work lies in a multi-step process under a biorefinery framework based on a dedicated perennial herbaceous feedstock with minimum agrochemical inputs and high yields that has not been exploited as lignocellulosic biomass.

The present study aims to evaluate the environmental impacts of a multi-functional biorefinery system co-producing bioethanol, high added-value products (e.g succinic acid) and energy from *Phalaris aquatica* L. considering three scenarios. In particular, the study goals are to (1) quantify the GHG emissions of the lignocellulosic-based biorefinery on a life-cycle basis (cradle-to-gate approach) and (2) to provide an energy analysis of the examined production process. The results in terms of GHG and energy balances will identify the preferable environmental characteristics of the bio-process, thus enabling the biorefinery's potential future commercial application.

Methodology

Goal and system boundaries

The LCA methodology was based on the four basic steps following the ISO 14040 including the goal, scope and boundary definition, the life cycle inventory analysis, the life cycle impact assessment and the results interpretation. According to the LCA results the environmental assessment of a product through its life cycle is carried out [14].

The goal of this study is to perform a "cradle to gate" analysis evaluating the environmental profile of a biorefinery co-producing bioethanol and succinic acid. More specifically, the present LCA study