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Original Research Article

Life cycle analysis and soil organic carbon balance as methods for assessing the ecological sustainability of 2nd generation biofuel feedstock

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ABSTRACT

The Life Cycle Assessment (LCA) method is the instrument of choice for quantifying environmental impacts; in particular, it is useful for estimating greenhouse gas (GHG) emissions associated with bioethanol production from agricultural residues such as straw. The LCA methodology considers process steps across bioethanol production from the crude feedstock to the standardized product bioethanol. However, agro-ecological constraints concerning raw material availability, such as the long-term conservation of soil fertility through the incorporation of straw on the field, are not taken into account within current LCA methodologies. Therefore, in this study, a method for soil organic carbon balancing was applied to ensure the sustainable supply of biomass. In addition to the GHG balance of bioethanol production from straw, the potential availability of straw for energy conversion was estimated on the regional level for Germany and its Federal States. The results of the GHG balance were heavily dependent on the chosen allocation method between grain and straw, and the amount of straw available for potential use as an energy source was largely determined by the structure of existing agricultural production. Potential regions for a 2nd generation bioethanol plant based on the available quantity of feedstock straw are shown in a case study for the German provinces.

Introduction

Within the European Union (EU), 2nd generation biofuels are assigned an enhanced role in achieving climate protection goals. Compared to 1st generation biofuels, 2nd generation biofuels are considered sustainable because the feedstock is not in competition with food production, and in many cases, they consist of agricultural residues. The production of bioethanol from straw is highly promoted in Europe by various research and demonstration projects [1,2]. As part of the EU sustainability framework, the Renewable Energy Directive 2009/28/EC (EU-RED) includes a set of mandatory criteria for monitoring and reporting requirements concerning biofuel production and use [3]. These sustainability criteria are also implemented in the Fuel Quality Directive 2009/30/EC, which includes mechanisms to monitor and reduce greenhouse (GHG) emissions by defining a minimum of 35% GHG savings obligatory for biofuels in comparison with fossil fuels; the savings increase to 50% in 2017 and 60% in 2018 for new biofuel plants. The so-called 2nd generation biofuels, for example, produced from lignocellulosic residues, would receive double credits in regards to the mandatory targets in the EU directive as they are produced from residues [4]. Biofuels are necessary to fulfill the sustainability criteria and should be required in the energy portfolio so that they gain financial or fiscal support. Concerning biomass feedstock, requirements for good agricultural and environmental conditions are necessary and included within the EU cross compliance rules of the Common Agricultural Policy (CAP). Guidelines were composed such that the calculation methodologies of soil organic carbon (SOC) and carbon stocks in vegetation for the different land use categories were fixed [5].

Although straw is primarily considered an agricultural waste material by the biofuel industry, straw usage has benefits that can be identified. When left on the field, straw significantly contributes to the development of soil organic carbon and further contributes to erosion control and soil fertility. Straw is also used as bedding in animal husbandry. This may lead to a competitive situation between animal husbandry and the biofuel industry. Above all, balanced soil organic carbon content in arable soils is essential for the long-term preservation of soil functions. The starting point for the determination of the relationship between soil organic carbon formation and degradation in agricultural soils is the soil organic carbon balance. When straw is used as a bioethanol feedstock, the retention of straw on the field, which ensures soil

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organic carbon reproduction, is an important ecological constraint that must be considered in the calculation of raw material potentials for bioethanol production. Hence, an evaluation of the system that only applies a Life Cycle Assessment (LCA) is not sufficient for this goal because it does not consider the soil organic carbon balance and ecological raw material availability. This was also recognized by Brandao et al. [6], who stated that there are only a few studies that consider SOC changes parallel to LCA and that this issue needs to be considered further because of significant differences in the way that various energy crops affect soil [6]. Humpenöder et al. [7] also draw attention to the coherence of carbon balances in LCA and carbon stocks in soil as a matter of land use change [7]. The cultivation of bioenergy crops can lead to soil organic carbon sequestration, as was shown for the case of miscanthus [8]. Besides miscanthus, switchgrass, and other perennial bioenergy crops are also known to promote soil organic carbon sequestration [9–12]. Perennial bioenergy crops increase soil carbon levels in contrast to conventional agricultural systems. Hence, perennial cropping systems are expected to enhance the productivity of subsequent crops planted on these areas [11]. This shows that there are opportunities to combine bioenergy production and the maintenance of soil quality via increases in soil organic carbon. The benefits that may result, however, are likely dependent on how the cropping systems are designed, which also may affect the availability of straw. Therefore, the sustainable availability of raw materials was assessed using the soil organic carbon balance as an additional tool in this paper. The amount of exportable straw was estimated using a combination of LCA and soil organic carbon balance techniques to ensure that soil quality will not be negatively affected.

Life cycle analysis of bioethanol production from straw

An LCA for the production of bioethanol from cereal straw was performed as the starting point of this study. The focus of the assessment was on determining GHG emissions associated with the production process, from the crude feedstock to the standardized bioethanol product, which were accounted for in CO_2 equivalents. The methodological approach used was guided by the International Organization for Standardization ISO standard 14040 for LCA. According to ISO 14040, system boundaries are determined first. Subsequently, a Life Cycle Inventory (LCI) is created, and then, the LCI results are merged into an environmental impact assessment. Additional interpretation and analysis of the results is also a part of the LCA method described in ISO 14040. In the following section, the LCA methodology will be described in detail and the results of each step are displayed starting with the system boundaries of the LCI and ending in the effects assessment.

Methods

The fundamental objective of an LCA is to conduct an inventory of all input and output streams connected with a product system, which consists of several process units. Based on the LCI, the environmental impacts associated with the product can be quantified. The product system is studied from the acquisition of raw materials to recycling or disposal; thus, the entire ecological life cycle is taken into account. The scope of the eco-balance analysis can vary depending on the system boundaries. In the present study, the definition used for the investigated system is shown below. The following diagram represents the sequence of the methodological LCA study according to ISO 14040 [13] and the application areas of an LCA (see Fig. 1).

Goal and scope

The aim of this LCA was to evaluate the present GHG emissions from the production of 2nd generation bioethanol by enzymatic saccharification of cereal straw and to compare these emissions to the fossil fuel reference defined in DIN EN 228. All process steps involved in the production of ethanol were considered in the assessment, from initial agricultural cultivation of biomass to the sale of biofuel at the gas station. The use of the fuel was not included in the present approach. Fig. 2 shows the simplified system boundary for the LCA of bioethanol from straw.

Fuel consumption for agricultural machinery (sowing, tilling, harvesting), as well as pesticide and fertilizer manufacturing and usage, are essential inputs for the process step of biomass cultivation. The biomass is supplied through agricultural operations and transport of straw from agricultural land to the bioethanol processing plant. In a sensitivity analysis, the impact of various transport distances was examined for the carbon footprint of the resulting bioethanol. The most important step is represented by the biomass conversion efficiency of the bioethanol plant. The energy source used for processing affects the GHG balance of the final product. Biomass conversion processes and the allocation methods chosen for each step in the biomass cultivation significantly influence the net result. The inputs and outputs used for biomass cultivation have to be designated for the grain and the straw. Moreover, an allocation scheme must be established for the resulting lignin-residue by-product and ethanol production from the bioethanol conversion process. A sensitivity analysis was performed in the present study for the allocation between grain and straw, where the following allocation variants were compared:

- No allocation: inputs and outputs were allocated 100% to wheat grain.
- Allocation based on mass balance: the starting point was a wheat grain yield of 6.4 t/ha and a straw yield of 5.1 t/ha. Consequently, 44% of the inputs and outputs were allocated to wheat straw.[1]
- Allocation by market value: the starting point was a wheat price of 199 €/t and a straw price of 70 €/t. Therefore, 26% of the inputs and outputs were assigned to wheat straw.[2]
- Allocation by calorific value: the base was a calorific value of 17 MJ/kg for wheat and 17.2 MJ/kg for straw. Approximately 50% of the inputs and outputs were assigned to the straw.

The aim of this analysis was to show the extent to which the GHG balance of bioethanol production is dependent on the chosen allocation method. The differentiation between primary and secondary products, in general, is still a controversial topic in LCA methodology [14–16]. Methodological proposals of the European Commission consider allocation by calorific value as the method of choice for biofuels [3]. Because of the strong influence of the chosen allocation method on the balancing results, other methods should not be ignored and the impact of each allocation method on the net result should be weighed. In the setup of the LCA framework, the functional unit is defined. The functional unit essentially describes the utility value of the product to be accounted for [13]. For this work, 1 MJ energy content of biogenic ethanol ex plant was chosen as a functional unit. All results of the LCA are presented in relation to the functional unit. The construction of infrastructure

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[1] Based on averaged central European yield and agricultural practices.

[2] Wheat price based on averaged price for sort US No. 2 Hard Red Winter Prd. Prot.1FAO, Crop Prospects and Food Situation 2008–2012; straw price based on averaged central European agricultural cost structures and average figures from the Association for Technology and Structures in Agriculture (KTBL), Germany.