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Research paper

Environmental sustainability assessment of bioeconomy value chains

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ABSTRACT

Bioeconomy has gained political momentum since 2012 when the European Commission adopted the strategy "Innovating for Sustainable Growth: A Bioeconomy for Europe". Assessing the environmental performance of different bioeconomy value chains (divided in three pillars: food and feed, bio-based products and bioenergy) is key to facilitate solid and evidence-based policy making. The objectives of this work were: (1) to map and analyse accessible LCA data related to bioeconomy value chains in order to identify knowledge gaps; (2) provide a more robust and complete picture of the environmental performance of three bioeconomy value chains (i.e. one per each bioeconomy pillar). This analysis reveals that apart from few products (such as liquid biofuels, some biopolymers and food crops) the environmental assessment of bioeconomy value chains is still incipient and limited to few indicators (e.g. Global Warming Potential and energy efficiency). In this study, a harmonised procedure – the Product Environmental Footprint (PEF), which includes fourteen impact categories – is used to estimate the environmental performance of three exemplary case studies which are inter-related due to the use of sugar as feedstock: sugar (food and feed), bio-based ethanol (bioenergy) and polyhydroxyalkanoates (bio-based product). Results highlight the strong need for methodological harmonisation and coherence for LCA of bioeconomy value chains.

1. Introduction

The bioeconomy concept refers to the sustainable exploitation of renewable biological resources for the production of food and feed, bio-based products and bioenergy [1] – the "three pillars" of the bioeconomy. It includes several industries and sectors: agriculture, forestry, fisheries, food, pulp and paper production and part of the chemical, biotechnological and energy industries. The European bioeconomy has gained political momentum and strategic importance. In 2012, the EU bioeconomy had a turnover of nearly 2 € trillion, employed more than 22 million people (i.e. 9% of total employment in the EU) and presented a strong innovation potential [2]. In the same year, the European Commission reaffirmed its commitment to the bioeconomy through the communication: "Innovating for Sustainable Growth: A Bioeconomy for Europe" [3], highlighting the unique opportunity to accomplish economic growth while guarantying resource security and efficiency through smart and sustainable use of renewable biological resources. So far, 16 countries in the EU have adopted action plans and measures in support of the bioeconomy.

This communication includes both a strategy and an action plan. Three of the main challenges addressed in the strategy – the management of natural resources sustainably, the reduction of the dependence on non-renewable resources and the mitigation and adaptation to climate change – are directly related to a progressive switch from the current fossil fuel-based economy to a more bio-based one. Towards this change, it is essential that an increasing share of biomass is made available to meet European demand for production of food and feed, bio-based products and bioenergy.

Such an increasing mobilisation and use of biomass has economic, social and environmental implications. This paper focused on the environmental implications. Assessing the environmental performance of different bioeconomy value chains is important to facilitate evidence-based policy making. The broadly accepted and extensively used Life Cycle Assessment (LCA) methodology was selected to quantify impacts along bioeconomy value chains. It includes all processes from the extraction of resources to the end-of-life – "from cradle to grave" [4] within the boundaries of the

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study. A remarkable number of LCA-based studies have been conducted to evaluate the environmental profile of different bioeconomy value chains. However, these are often based on different methodological assumptions and use data of different nature and quality. This makes the results from these evaluations virtually incomparable. A clear quantitative understanding of the environmental aspects of bioeconomy value chains is thus currently missing.

The objectives of this work were: (1) to map and analyse accessible LCA data relative to bioeconomy value chains in order to identify knowledge gaps; (2) to provide a more robust and complete picture of the environmental performance of three exemplary bioeconomy value chains (i.e. one per each bioeconomy pillar).

This paper is organised as follows: Section 2 describes the methodology and the criteria used for mapping existing LCA-based studies and perform new ones. Section 3 provides the results of the mapping and the LCA modelling for three exemplary case studies which are inter-related due to the use of sugar as feedstock: sugar production (for the food and feed pillar); bioalcohols production via fermentation (for the bioenergy pillar); and polyhydroxyalkanoates (PHAs) production (for the bio-based product pillar). The conclusions of the work are drawn in Section 4.

2. Methodological approach

2.1. LCA mapping exercise

This paper builds upon work conducted within the FP7 project "Set-up of a Bioeconomy Observatory – Bioeconomy Information System and Observatory (BISO)", [5]. In particular, a list of key bioeconomy value chains (see Table 1) for each pillar was selected and analysed to identify existing and prospective technologies for biomass conversion and measure its environmental performance. The criteria for selecting the value chains are: importance in the global market, representativeness and/or relevance for possible competition with similar fossil-based products.

LCA is a widely accepted decision support method to assess environmental impacts along all stages of the life-cycle of a given product system. Different impact assessment methods can be used when conducting LCA studies. Each of these methods has a specific set of impact categories and characterisation factors. The most used impact assessment methods include: ReCiPe, CML2001, Eco-indicator 99, IMPACT 2002+ and TRACI [6,7]. In addition to LCA, several other life cycle-based environmental accounting methods and standards exist. The European Commission recommends the use of the LCA-based Product Environmental Footprint (PEF) [8] method to evaluate the environmental performance of product-system supply chains [9]. A comparison of the robustness of the PEF against other most used methods and standards for environmental accounting can be found in Ref. [10]. The PEF method was used as the reference for our LCA data mapping. It includes fourteen impact categories in order to provide comprehensive evaluation of the environmental performance of value chains (see Table 2).

The literature review conducted in this study revealed that it is a common practice to limit the number of impact categories considered to facilitate the overall assessment and interpretation of the results, as well as to limit data collection efforts. However, such an approach can lead to inaccurate and misleading conclusions [11]. Thus, all fourteen PEF-recommended impact categories were considered in this assessment of three exemplary bio-based value chains. The identification of knowledge gaps in the reviewed literature was done through a mapping of accessible LCA studies that provided an evaluation of the environmental performance of the selected bioeconomy value chains. The selection of these LCA studies was performed using the following criteria:

- studies conducted under the EU framework programmes for research [12];
- peer-reviewed literature;
- priority was given to studies accounting for the highest number of impact categories and studies reporting environmental impacts calculated in line with the PEF methodology;
- studies with obsolete, incomparable (i.e. percentages or weighted figures) or dubious quality data were excluded.

The LCA data mapping was performed by identifying the minimum and maximum reported values for each impact category (see Section 3). The purpose of this study was not to discuss the correctness of the methodological assumptions and choices done in the reported studies. However, a discussion on the effect of some key LCA assumptions on the final result is provided in Section 3 and some recommendations are given in Section 4.

2.2. LCA of exemplary bioeconomy value chains

The objective of performing a LCA can be either (1) measure the consequences of altering a system, or (2) analyze the environmental impacts along a product's life cycle. These two goals are frequently tackled by consequential LCA and attributional LCA, respectively [13]. The comparison of data and results obtained under such different methodological assumptions is challenging and sometimes even impossible. For that reason, the second objective of this paper was to develop comprehensive LCAs of selected bioeconomy value chains (one for each pillar) using the

Table 1
Selected bioeconomy value chains within the BISO FP7 project.

Food & feed	Bioenergy		Bio-based products
Product	Product	Via	Product
Eggs	Biodiesel	Transesterification	Lactic acid
Milk	Bio-based alcohols	Fermentation	Acetic acid
Sugar	Small-scale heat	Direct combustion	Adipic acid
Tomato	Large-scale heat	Direct combustion	Succinic acid
Wheat	Electricity	Direct combustion	1,3-Propanediol
Wine	CHP	Direct combustion	Glycerol
	Biofuels	Gasification	Polylactic acid (PLA)
	Hydrogen	Gasification	Polyhydroxyalkanoates (PHAs)
	CHP	Gasification	Amino acids
	Biodiesel	Hydrogenation	Paper
	CHP/Fuel	Torrefaction	
	CHP	Anaerobic digestion	
	CHP/H_2	Pyrolysis	

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