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A review of the sustainability of algal-based biorefineries: Towards an integrated assessment framework

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A B S T R A C T

Algal-based bioenergy products have faced multiple economic and environmental problems. To counter these problems, algal-based biorefineries have been proposed as a promising solution. Multiple environmental and economic assessments have analyzed this concept. However, a wide variation in results was reported. This study performs a review to evaluate the methodological reasons behind this variation. Based on this review, four main challenges for a sustainability assessment were identified: 1) the use of a clear framework; 2) the adaptation of the methodology to all stages of technological maturity; 3) the use of harmonized assumptions; 4) the integration of the technological process. A generic methodology, based on the integration of a techno-economic assessment methodology and a streamlined life cycle assessment was proposed. This environmental techno-economic assessment can be performed following an iterative approach during each stage of technology development. In this way, crucial technological parameters can be directly identified and evaluated during the maturation of the technology. The use of this assessment methodology can therefore act as guidance to decrease the time-to-market for innovative and sustainable technologies.

Contents

Abbreviations: TEA, Techno-Economic Assessment; TRL, Technology Readiness Level; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; GWP, Global Warming Potential; ETEA, Environmental Techno-Economic Assessment

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1. Introduction

Algal-based biorefineries have been proposed as a promising approach to enhance the microalgae industry. The valorization of multiple co-products could improve the economic viability of microalgal-based biofuels [1]. However, further investigations concerning the economic feasibility and the environmental impact are required [2]. Multiple studies have performed economic or environmental assessments in order to accurately quantify these impacts. The main objective of this study is to propose a new methodology, which can harmonize the different assessments from a methodological point of view. Such a harmonized assessment enables the comparison of the different proposed production processes to permit a clear view on the commercialization potential of microalgae-based biorefineries.

Microalgae are photosynthetic microorganisms that can be found in all existing ecosystems [3]. A study by Guiry [4] estimated the total amount of algal species to be 72,500. Due to this large variety in species, multiple applications exist, such as food, feed and energy [5]. However, only approximately 15 species of microalgae are currently used on a commercial level. Therefore, microalgae are still considered as an untapped resource for a biobased economy [6].

Compared to other bioenergy feedstocks, microalgae have a large biomass productivity and high lipid content [7]. Therefore, the application of microalgae biofuels has gained a lot of attention during the last decades [8,9]. However, several economic and environmental constraints concerning its commercialization have been identified; examples are the high production costs compared to fossil fuels and the high water consumption during cultivation [10,11]. Moreover, the production of biofuels in general has become controversial, for instance due to the food-versus-fuel debate and indirect land-use change emissions. If the biofuel industry cannot ensure that its environmental impact is significantly lower than that of the fossil fuels it substitutes, the main reason of existence for this industry is at risk [12].

A solution to these environmental and economic problems of biofuels could be the supplementary valorization of other biochemical components from the microalgae biomass [1]. This algal-based biorefinery perspective has been suggested by multiple authors [13,14]. Also other biomass feedstocks have been discussed for the application of a biorefinery concept [15]. The algal-based biorefinery should follow the cascading principle, which prioritizes the production of high-value products before energy products [16]. The sustainability of this concept has been examined by multiple studies, in order to prevent the problems that slowed down the research and development of algal biofuels. Multiple authors have emphasized the need for harmonization efforts as the results of these economic and environmental assessments are widely varying [17,18]. Such a harmonization study was performed by Sun et al. [19] in order to decrease the variability in production costs between 12 economic studies. The authors concluded that the variety could be attributed to disparate assumptions and uncertainties in economic and process inputs. The differences in process inputs have been reviewed by multiple studies, such as Williams and Laurens [20]. However, only a few papers, such as Collet et al. [17], reviewed the disparate methodological assumptions in depth. Moreover, most of these reviews were limited to one dimension of sustainability. Harmonization efforts between a techno-economic and environmental assessment of algal-based biofuels have been undertaken in order to enable the study of tensions and tradeoffs between the different sustainability dimensions [21]. However, an in-depth review, including the integration of these different dimensions, is still lacking.

This paper fills this gap by reviewing the methodologies used to assess the sustainability of algal-based biorefineries. The different methodological choices and assumptions are discussed in order to identify the main methodological reasons for the varying results. This review generates four main challenges for a harmonized and integrated methodology. Based on these challenges, a generic integrated assessment of the sustainability of algal-based biorefineries is proposed. This strategy was illustrated in Fig. 1.

2. Methodology

This review covers quantitative sustainability assessments from an environmental, an economic and a combined perspective. No papers were encountered which examined the social aspects of algal-based biorefineries; therefore, this dimension could not be included. The assessments included in this review originate from scientific peer-reviewed articles found in different scientific databases (EBSCOHOST and Google Scholar).

Sixty-four environmental assessments, forty economic assessments and twenty assessments, which combined or integrated both dimensions, were included. The methodology used for the assessments was reviewed in detail, focusing on the framework of the methodology itself, the scope of the assessments, the inclusion of uncertainties, the assumptions and the static or dynamic character of the technological process, which was assessed. Based on the differences between the different assessment methodologies on all these categories, four main challenges with which the different studies have to deal with are identified. Three of these challenges are directly related to the differences between the different studies within one sustainability dimension. The fourth

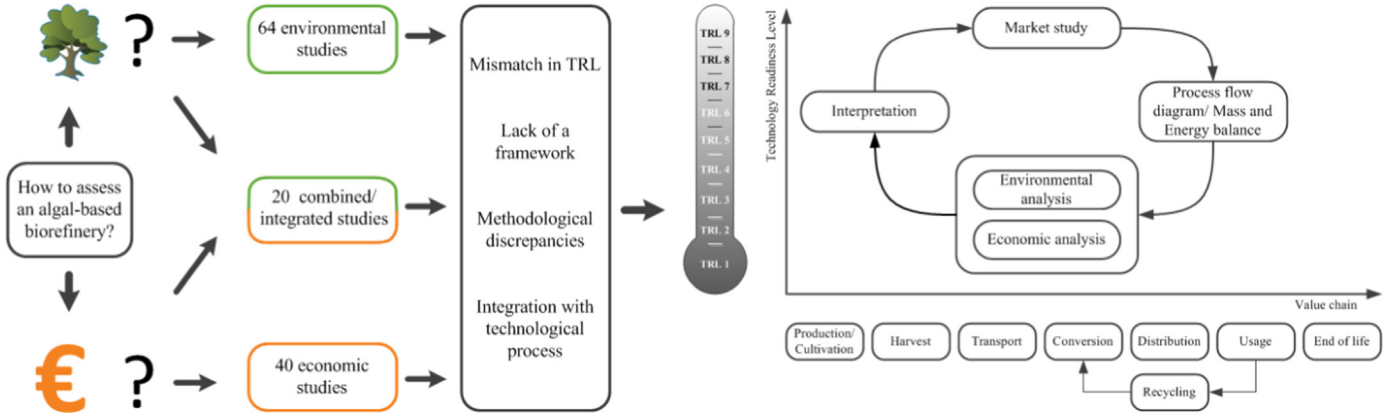

Fig. 1. Graphical abstract of this study.

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