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A review of sustainability indicators for biobased chemicals

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ABSTRACT

Companies dealing with chemical products have to cope with large amounts of waste and environmental risk due to the use and production of toxic substances. Against this background, increasing attention is being paid to "green chemistry" and the translation of this concept into biobased chemicals. Given the multitude of economic, environmental and societal impacts that the production and use of biobased chemicals have on sustainability, assessment approaches need to be developed that allow for measurement and comparison of these impacts. To evaluate sustainability in the context of policy and decision-making, indicators are generally accepted means. However, sustainability indicators currently predominantly exist for low-value applications in the bioeconomy, like bioenergy and biofuels. In this paper, a review of the state-of-the-art sustainability indicators for biobased chemicals is conducted and a gap analysis is performed to identify indicator development needs. Based on the analysis, a clear hierarchy within the concept of sustainability is found where the environmental aspect dominates over economic and social indicators. All one-dimensional indicator-sets account for environmental impacts (50%), whereas two-dimensional sets complement the environmental issues with economic indicators (34%). Moreover, even the sets encompassing all three sustainability dimensions (16%) do not account for the dynamics and interlinkages between the environment, economy and society. Using results from the literature review, an indicator list is presented that captures all indicators currently used within sustainability assessment of biobased chemicals. Finally, a framework is proposed for future indicator selection using a stakeholder survey to obtain a prioritized list of sustainability indicators for biobased chemicals.

1. Introduction

The chemical industry must cope with large amounts of waste and environmental risk due to the use and production of toxic substances. About 60% of chemicals are hazardous to human health or the environment in the EU [1]. Legislations like REACH (Registration, Evaluation and Authorization of Chemicals) and RoHS (Restriction on Hazardous Substances) have been introduced to stimulate the use of less hazardous chemicals. The concept of 'green chemistry' corresponds to these policies and is defined as "the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances" [2]. The definition of green chemistry is based on twelve principles, designed to help achieve sustainability, formulated by Anastas and Warner (1998) [3]. One of these principles is the use of renewable feedstocks, which can be translated into practice by the use and production of biobased chemicals, such as bioplastics and specialty chemicals.

Biobased chemicals belong to the biobased economy, where organic matter (i.e. biomass) is converted into materials and energy. Biomass as a feedstock offers opportunities to deal with increasing prices of fossil feedstocks and their decreasing availability [4]. The focus in the biobased economy is currently shifting from bioenergy and biofuels to the production of high value biobased products, including biobased chemicals [5]. Biobased products are products wholly or partly derived from biomass, such as plants, trees or animals, with the biomass potentially undergoing physical, chemical or biological treatment [6]. In 2014, the EU turnover of manufacturing biobased chemicals, pharmaceuticals, plastics and rubber was 130 billion euros, compared to 30 billion euros for liquid biofuels and 10 billion euros for biobased electricity [7].

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The emerging biobased economy is often associated with increased sustainability [8]. However, the use of biomass can also lead to negative consequences, for example by driving up food prices through increased competition for land and resources, or by increasing greenhouse gas (GHG) emissions through land use change [9,10]. To ensure that biobased products become or remain more sustainable than their fossil fuel based counterparts, a systematic and interdisciplinary assessment approach is needed [8]. The current trend is to move away from multidisciplinarity towards transdisciplinarity and holism, where adequate sustainability evaluations account for the interactions and interdependencies across the different sustainability themes [11]. Criteria and indicators can be used as flexible and user-friendly techniques to evaluate and integrate environmental, economic and societal impacts. Sustainability indicators are needed to translate sustainability into a practical set of measures and are frequently used for policy- and decision-making [12–14].

International attempts to provide and stimulate sustainability within the general bioeconomy started with the development of criteria and indicators for sustainable forest management [5]. These first environmental assessments were designed as a result of the concerns about tropical deforestation. Later, sustainability frameworks for biofuels and bioenergy followed [5]. More general sustainability frameworks were constructed through initiatives and projects like UNEP-SETAC (2009), the Global-Bio-Pact (2012), ORNL (2013) and BioSTEP (2016). As sustainability assessment became more popular, a significant variety of mostly environmental stand-alone indicators were developed, like the cumulative energy demand (CED) and the E factor [15,16]. Nevertheless, one indicator can never capture all aspects of sustainability.

Researchers are concerned with the development of indicators and frameworks for the assessment of sustainability. Singh et al. and Ruiz-Mercado et al. compiled an overview of indicators and indices for generic sustainability assessment of chemical processes and concluded that most assessments only evaluate one aspect of sustainability [12,17]. They argued that by using the indicators complementarily, interlinkages and dynamics between the different aspects of sustainability have been missed. Seuring and Müller, Lozano, Tang and Zhou, Seuring and Aktin and Gergin agree with these concerns regarding inadequate sustainable management [18–22]. If we narrow the broader sustainability scope down to a focus on biobased chemicals, no full overview or discussion of sustainability indicators currently exists.

The aim of this paper is to review existing indicator-sets, to classify the different indicators, and to define the gaps in sustainability assessments specifically for biobased chemicals. While assessing the sustainability of biobased chemicals, all indicators covering the full value chain from cradle to cradle should be considered [23]. A state-of-the-art review like this one is a crucial step towards a generalized set of indicators that can be used to assess and evaluate performances and to provide information on improvements or declining trends. These indicators should be uniform within the field of biochemistry, since they will provide information to decision-makers on formulating strategies and communicate achievements to stakeholders [24,25]. If more stakeholders use the same set of metrics, efforts involving data collection and the time required to assess the products will be reduced as a result of experience and knowledge sharing [26]. Moreover, a standardized set of sustainability indicators enables comparisons between biobased chemicals and facilitates policy recommendations. This paper focuses on biobased chemicals, taking into account the specific chemical- and biological characteristics of the products. Although some indicators can be used in all process industries, sector-specific indicators are often required to address specific features of each industrial sector [27].

The next section explains the method used to perform an adequate review of the current biobased chemistry indicators landscape. Existing indicators are defined, classified and the gaps in current literature are determined. The results are covered in the third section, followed by an extensive discussion and conclusion.

2. Method

This study is based on a systematic literature search, considering articles published up to and including 2017, using Boolean logic on ISI Web of Science (WoS) (Fig. 1). The initial query: 'biobased chemicals' AND 'sustainability indicators', yielded 130 results. Related search terms containing 'green chemistry', 'sustainability metrics' and 'sustainable decision making', enriched the dataset and were added as a necessary extension for the review. At this stage, 26 papers were considered relevant to include in this review study. Finally, additional queries based on the separate sustainability dimensions were included ('environmental sustainability', 'economic sustainability' and 'social sustainability'), and resulted in 12 extra papers for the final dataset. In total 38 papers were selected.

The decision for inclusion of articles is based on two criteria: (1) the focus on 'sets' of indicators instead of stand-alone indicators and (2) enclosing sets which assess only on product- and/or activity level. First, the included articles are selected based on the use of sets of indicators aiming for a sustainability evaluation of a biobased chemical. Research about stand-alone indicators is left out of the initial dataset, but articles about these stand-alone indicators were often necessary to clarify and complete the output of this analysis. Also, research articles about indicators used in the broader bioeconomy or chemical industry are not necessarily included, only if applied on a biobased chemical case study or considered relevant by other biobased chemical research applications. Second, the included indicator-sets are all developed for assessment on the product level of the chemical. Research that explores sustainable development more broadly, like on a company- or country-level, was excluded from the dataset.

The 38 papers that are included in this analysis to discuss a comprehensive selection of indicators is provided in Appendix A. The indicators are classified within the corresponding sustainability domain and assigned to a sustainability criterion. In the analysis, a distinction is made between 'method papers' and 'application papers'. The method papers provide new sets of indicators developed to evaluate the sustainability of biobased chemicals. The application papers apply (part of) the sets described in the method papers to business-cases within the biobased chemical industry.

The studies included for the gap analysis are analysed according to (i) the inclusion of different sustainability pillars (i.e. environment, economy and society), (ii) their focus (i.e. general sustainability, general biomass, chemicals and biobased chemicals), (iii) the overlap between indicators (derived from description and formula) and (iv) interlinkages between the sustainability domains. Based on the results of this review, an indicator list is presented that captures all indicators currently used in scientific literature for sustainability assessments of biobased chemicals (Appendix B).