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Residual biomass as resource – Life-cycle environmental impact of wastes in circular resource systems

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ABSTRACT

Within an envisioned circular bio-based economy, a key component is the valorization of biomass wastes and residues into valuable products. If the commonly used method of life-cycle assessment (LCA) is applied to such products, an update and adaptation of LCA practice is needed regarding potentially outdated assumptions of residual resources as free from environmental impact. This paper therefore presents and discusses LCA approaches to evaluating residual biomass as resources, and implications of different approaches to LCA results and decision-making. Based on an analysis of 31 LCA studies of bio-based products, and on a model for recycling in LCA, we discuss alternatives to zero-burden assumptions for biomass residues. The studied literature shows a variety of approaches to assessing the impacts of residues, including views of relevant characteristics and causality in primary production systems, and intended use and interpretation of LCA results. In general, acknowledging upstream impacts through a simple model of recycling and allocation entails that the environmental characteristics of primary production systems reflect on by-products and residues. We argue that LCA studies of residue valorization must recognize the potential value of residues by considering upstream impacts, and thereby avoid both misconceptions of residues as per default environmentally preferable resources, and unintentional support for high-impact primary production systems. Residues as resources require this adaptation in LCA practice in order to avoid misguided decisions for a low-impact, bio-based and circular economy.

1. Introduction

With limited natural resources globally and increasing pressure on ecosystems, one potential strategy to mitigate anthropogenic environmental impacts is to make better use of available resources. Based on this idea, a popular concept is that of the circular economy (Geissdoerfer et al., 2017) which refers to a society where resource flows are circular rather than linear and implies that all resources are used efficiently, materials are recycled, and little end waste is created. Another popular term is bioeconomy, or bio-based economy, which refers to a widespread use of biomass replacing fossil resources, and where efficient utilization of organic material and cascading use (Keegan et al., 2013) can play an important role (Bugge et al., 2016). In working with these ideas towards more efficient and circular biomass resource flows, the utilization and valorization of resources that were previously considered to be of low or no value is a key part (Murray et al., 2015).

As another expression of the aspiration to mitigate environmental pressure, life-cycle assessment (LCA) has become a popular tool to assess and compare the environmental impacts of products. The LCA method quantifies the use of resources and the emissions that arise throughout a product's life cycle, commonly referred to as from cradle to grave and defined by system boundaries. In LCA studies of waste and low-value residues, the practitioner must set the upstream system boundary, deciding where the study of the waste life cycle starts (Finnveden, 1999). One potential approach to this is a zero-burden assumption in which the activities that occurred prior to the generation or collection of the waste material, and consequently their environmental impacts, are left outside the system boundaries (Clift et al., 2000; Ekvall et al., 2007; Nakatani, 2014). The underlying logic requires the comparison of systems with identical amounts of waste, because then the upstream processes can be considered equal in the two systems, and their environmental impacts will not affect the intended comparison (Finnveden, 1999).

Though they do not necessarily follow the same logic, similar

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assumptions of zero-burden resources are present in LCA studies of waste and residue utilization today. One example in the area of biofuels is the EU renewable energy directive (2009/28/EC), which states that for calculations of biofuels' greenhouse gas emissions, waste raw materials "*shall be considered to have zero life-cycle greenhouse gas emissions up to the process of collection of those materials.*" Here, the assumption of zero burden refers to burden-free residual or waste biomass that is used as raw material in a product life cycle, and not to a comparison of waste treatment options for a certain amount and type of waste. Thus, it appears that another type of "zero-burden assumption" is present in practice (as is also pointed out by Oldfield and Holden, 2014; Oldfield et al., 2018; Pradel et al., 2016), and as can be exemplified by a number of recently published LCA studies (see e.g. Esteve-Turrillas and de la Guardia, 2017; Etxabide et al., 2016; Hajjaji et al., 2016; Husgafvel et al., 2016; Koller et al., 2013; Peñarrubia Fernandez et al., 2017; Ramirez et al., 2012; Summers et al., 2015).

The logic and applicability of zero-burden assumptions may however be affected by a shift towards circular resource systems, where waste is increasingly considered, utilized and studied as a resource with an economic value. In a recent study, Oldfield et al. (2018) discussed zero-burden assumptions for waste resources, and through examples of garden and food waste the authors showed that this is one of several method aspects in LCA which may be crucial to decisions regarding waste resources in a circular economy. As a similar example, Pradel et al. (2016) studied the paradigm shift in the waste status of wastewater sludge, and its implications to LCA. The authors concluded that the zero-burden assumption becomes debatable when sludge is no longer considered a waste material, and that it is not valid when sludge provides further functions in other product systems, e.g. by means of nutrient or material recovery. Similarly, Oldfield and Holden (2014) showed that the zero-burden assumption is prevalent but rarely discussed in studies of food-waste valorization, and argued that the assumption is not compatible with a recognition of the economic value of food waste. Further, in their LCA study of fuels made from residual fat, Seber et al. (2014) showed parallel calculations where tallow was considered burden-free, and where it was considered accountable for a small percentage of upstream GHG emissions from animal husbandry. Though only briefly addressed by the authors, the assumed environmental impact of tallow substantially affected the resulting GHG emissions of biodiesel fuel.

In order to avoid misguided decisions based on improper method choices in a growing circular economy, a clarification of the applications and implications of zero-burden assumptions in LCA is necessary. Where zero-burden assumptions are not valid nor useful, such as when the waste status of a material is uncertain or changing, an alternative approach for dealing with upstream impacts of residual biomass as resources is needed. The main purpose of this paper is therefore to present and discuss approaches in LCA for evaluating residual biomass as resources. Such approaches and method choices have implications to LCA results and decision-making, and the discussion is especially important in light of a potential future circular resource system which aims to mitigate anthropogenic environmental impact.

To this end, we discuss different LCA approaches to multi-functionality and wastes as resources, followed by a literature study and analysis of evaluation of residual biomass in LCA. The literature study comprises existing LCA studies on seven biomass processing industry sectors and an analysis regarding their methods for handling the multi-functionality of production systems, and more specifically their assigning of environmental impacts to residues. Findings from these studies are also discussed in relation to additional LCA literature which focuses explicitly on general method development and multi-functionality. By showing how previous studies of main products and production systems assign environmental impacts to residues, compared also to ideas from more methods oriented literature, we aim both to develop an understanding of the choices made by LCA practitioners concerning valuation of different residual materials, and to provide a first data inventory for upstream environmental impacts of residual biomass. The purpose is thus to discuss implications across a range of potential LCA applications and rationales.

2. Life-cycle assessment methods for residues and recycling

First, the definition of important terms such as waste and residue are introduced (2.1), followed by a review of potential lines of reasoning behind assumptions of burden-free resources within LCA (2.2).

2.1. Definition of by-products, wastes and residues

Defining materials as main, co- or by-products, or residues or wastes, is not straightforward, and depends on context. The concept of waste is defined in the European Union's Waste Framework Directive (2008/98/EC) as "*any substance or object which the holder discards or intends or is required to discard*". The directive also states criteria that define by-products and end-of-waste, the latter describing when a waste material ceases to be waste after recovery. Offering an alternative definition of waste in the context of LCA, Weidema (2001) suggested that "*a waste is an output that does not displace any other product*". This definition builds on, but offers a more precise distinction than, an economic basis where a waste is simply an output that does not provide economic value to the process from which it arose (Weidema, 2001), or an output that has a negative economic value (Guinée et al., 2004). Avoiding a focus on economic value, the definition of waste based on the potential further use of the material can be viewed as consistent with the ISO 14044 standard, where wastes are "*substances or objects which the holder intends or is required to dispose of*" (ISO, 2006; Pelletier et al., 2015).

In accordance with the definition of waste as an output material that is disposed of and not further utilized, we consider all biomass outputs that can potentially be further utilized as potential non-waste products. This starting point lets us investigate upstream environmental impacts for any biomass that could be, or has been, argued to be burden-free due to a perceived waste status, which is in line with the idea of circular economy where wastes to a greater extent should be considered resources for further use. Therefore the term residual biomass as used in this paper includes any biological material that originates from processing of biomass, except for main products which are originally intended to be produced. While this definition does not say which particular materials are wastes and which are not, it provides guidance within a certain context. As wastes and residues are not defined by physical properties or chemical composition but rather by process economics, trade and markets, or even perception, what constitutes residual biomass changes over time and across space — a product can be both a co-product and a waste in different places, and it can go from being residual biomass to being one of several desirable, marketable co-products. As a complement to residual biomass, by-products and residues is used here to indicate a span of potential valuation, waste status and utilization of the biomass investigated.

2.2. Zero-burden assumptions and recycling

As mentioned in the introduction, the original definition and application of a zero-burden assumption was for comparisons of waste management options in systems with identical waste