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LCA and Eco-design: Consequential and Attributional Approaches for Bio-based Plastics

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Abstract

Against the background of climate change and finite fossil resources, bio-based plastics have been in the focus of research for the last decade and were identified as a promising alternative to fossil-based plastics. Now, with an evolving bio-based plastic market and application range, the environmental advantages of bio-based plastic have come to the fore and identified as crucial by different stakeholders. While the majority of assessments for bio-based plastics are carried out based on attributional life cycle assessment, there have been only few consequential studies done in this area. Also, the application of eco-design strategies has not been in the focus for the bio-based products due to the prevailing misconceptions of renewable materials (as feedstock for bio-based plastics) considered in itself as an 'eco-design strategy'. In this paper, we discuss the life cycle assessment as well as eco-design strategies of a bio-based product taking attributional as well as consequential approaches into account.

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Keywords: Bio-based plastics; Eco-design; Consequential LCA; attributional LCA

1. Introduction

Plastics have become an indispensable material in this current age with a versatile range of applications in sectors like automobiles, packaging, electronic goods and more. The global production of plastics has increased in the past 50 years and it is expected to double again over the next two decades [1]. Even though the plastics have changed our lives with its wide range of benefits like durability, strength and versatility, most of these conventional plastics are manufactured primarily from fossil resources like crude oil, which are not only limited but also have a significant influence on the global climate change. Apart from its feedstocks, the uncontrolled usage of conventional plastics has resulted in plastic pollution, with plastics ending up in oceans and open spaces, thereby posing an inevitable threat to the nature. In the quest of finding a sustainable alternative to the conventional plastics, bio-based plastics made out of renewable raw materials have taken the center stage in the past two decades. Bio-based plastics, which are derived partly or completely from renewable resources like sugarcane, sugar beet, castor bean, maize and so on, even though with a 6% of the market presence in the global plastics market, have seen an increasing growth and is projected to increase its presence in the next two decades [2]. However, there have been several questions posed to the bio-based plastics producers as to whether bio-based plastics could be a sustainable alternative to the conventional fossil-based plastics on a long term [3], as the bio-based plastics has got its own share of challenges like the sourcing of feedstocks, land use, methods of cultivating the biomass, usage and disposal of the bio-based plastics. It is always necessary to analyze the complete value chain of a product made out of bio-based plastics before making comparisons with its conventional counterparts. It is important to investigate the direct and indirect environmental impacts

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throughout the value chain of the products, even before its production. In order to improve the marketability of the bio-based plastics, it is also important to analyze the mechanical and chemical properties of the raw materials used in the production of bio-based plastics and the performance of the products to increase the usage of the same, extending its life before the disposal. Apart from the design of the products, it is important to communicate transparently to the stakeholders (businesses and consumers) on the performance of the developed products, which is insufficient as of now [4]. Eco-design is a well-known approach in designing products along with the consideration and integration of the environmental impacts of the product system, even before its development phase [5]. Eco-design also helps us understand the thinking behind the selection of the raw materials, technologies and processes in a product system, by taking material and energy efficiency into account [6]. While Eco-design helps us understand the quality and design aspects of a product, Life Cycle Assessment (LCA) is an internationally standardized method to determine the potential environmental impacts of a product over its entire lifecycle. However, there is a growing consensus on performing LCA on bio-based products not only by the well-known attributional approach (Attributional LCA or ALCA) but also using the consequential approach (Consequential LCA or CLCA) in order to avoid the problem of allocation in multi-functional bio-based systems [7] and also include the activities that have indirect implications on the product system. While there have been many ALCA studies conducted on biopolymers [8, 9, 10], which are used to produce bio-based plastics, very few have been done using a consequential approach [11, 12, 13]. Moreover, most of these LCA studies are used as either a communication tool for the environmental performance of the biopolymers [8] or one-on-one comparison with its conventional counterparts. There is less emphasis in these studies on the design aspects, physical and chemical properties of the products produced from these biopolymers as well. Integrating eco-design strategies with the results of ALCA and CLCA will give the product developers, manufacturers and the consumers, a better understanding and a complete picture on the quality and environmental impacts of a product, thereby preventing false claims [14] and greenwashing. This paper will provide a short overview on the different LCA studies conducted on the biopolymers and different studies that integrate LCA and ecodesign to improve the product characteristics on a long term. This paper will also list the challenges and recommendations in integrating eco-design with the results of ALCA and CLCA of bio-based plastics. This paper is, however not a review or a critique on the methodology or the structure of considered LCA or ecodesign studies but the findings from these will help to identify recommendations to integrate the results of LCA with the eco-design of bio-based plastics.

2. Research background

Bio-based plastics are defined as ready to use blends, which consists of biopolymers as well as additives, according to Endres and Siebert-Raths [15]. To understand how one can integrate eco-design strategies with the results of ALCA/CLCA (addressed generally as LCA from now on) for a sustainable production of bio-based plastics, it is important to study and investigate the previous LCA and eco-design studies on biopolymers. In this paper, observations from the past studies on biopolymers are listed as a case for integrating eco-design with LCA results of biopolymers.

2.1. LCA of biopolymers

LCA is used these days not only to assess the direct environmental impacts of a product system and compare them with other products but also influence and initiate policy and marketing decisions. Therefore, the interpretation (by the experts and consumers) and the communication of the Life Cycle Impact Assessment (LCIA) results from LCA have become important, more than ever. With regards to the LCA studies of bio-based plastics, there have been instances [8] of selecting and giving importance to few impact categories like Global Warming Potential (GWP) and Non Renewable Energy Usage (NREU), which showed positive tendencies in comparison to the conventional plastics. There have also been instances of setting system boundaries for the selected biopolymers from cradle to gate [9], which involves only in the production of the biopolymers but neglect the use and End of Life (EoL) stages, which can have a significant influence on the total environmental impacts of a product system. This section gives an overview on some of the LCA studies done for biopolymers.

Most of the LCA studies done for biopolymers so far follow the attributional approach. Attributional approach involves in accounting the impacts of a product system without considering any external influences. It attempts to provide information on the portion of global burdens that can be directly associated with a product (throughout its lifecycle) [16]. The product system in an ALCA ideally contains processes that are directly linked by flows to the unit processes that supplies the functional unit [16]. It uses inventory data for its LCA from the material suppliers or average data (for example: Average electricity mix of a region).

For the ALCA of biopolymers, instead of explaining each and every LCA study done so far, it has been decided to consider two studies for this paper that reviewed some of the ALCAs done for the biopolymers. The two studies are “Life Cycle Assessments of biodegradable, commercial biopolymers” by Yates & Barlow [17] and “Sustainability assessments of bio-based polymers” by Troy. A. Hottle et al. [18]. Yates & Barlow [17] reviewed published ALCAs of biopolymers such as Polylactic acid (PLA), Polyhydroxyalkanoate (PHA) and thermoplastic starch (TPS) in comparison to conventional polymers like Polyethylene Terephthalate (PET), Polystyrene (PS), High-density polyethylene (HDPE), Polypropylene (PP). Hottle.et.al [18] is a similar study that reviewed published ALCAs and already existing LCA databases that quantify the environmental impacts of biopolymers such as PLA, PHA and TPS in comparison to the conventional polymers. Yates & Barlow also discuss in detail about the waste management and EoL options for different biopolymers after its use phase [17]. Some of the findings from these two publications (with and without having conventional polymers as a benchmark) are:

- Inconsistencies in the LCA results due to the assumptions about system boundaries and allocation methods
- Lack of information on the data sources used in the LCA of biopolymers
- Different boundary settings (between natural and technical systems), different feedstocks and different production technologies between studies
- The incorporation of landuse change (LUC) between studies is not consistent
- Discrepancies in energy consumption due to geographical differences and corresponding energy mixes
- Studies that looked only on selective impact categories drew conclusions based on material preferences (GWP and NREU of biopolymers better than conventional polymers)
- Including EoL and use phase provide a comprehensive estimate of the total impacts but there are large uncertainties associated with the consumer behavior in use phase and inventory data in EoL processes
- Potential benefits of biopolymers with regards to different impact categories can't be realized until material and energy consumption of farming and production processes are reduced
- Given the fact that biopolymers are relatively new to the global plastics market, any comparison with the conventional polymers must take the status of technologies and market presence into account
- Environmental impacts quoted for conventional fossil-based polymers are not consistent between studies which can have an adverse effect on the results

The consequential approach, also known as 'change oriented approach', tries to provide information on the environmental impacts that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product [19]) [16]. Product system analyzed in this approach consists of processes that are actually affected by cause-and- effect chain whose origin is a particular decision [16]. CLCA uses data from the suppliers, only if it is not constrained (insofar as it can respond to an increase in demand with an equal increase in supply) or uses marginal data (marginal suppliers responding to a change in demand) [16].

CLCAs analyze the product system, keeping in mind of the market mechanisms, state of advancement of technologies and the utilization of co-products indirectly affecting the considered product in case of a multi-functional product system, thereby influencing policy and decision making.

In the case of bio-based products, CLCAs help in understanding the implications in the usage of feedstocks and the decisions that indirectly affect the production of feedstocks. The CLCA also has the potential to influence the policy framework for the global production of bio-based plastics. Even though there have been many CLCA studies done for bio-based products like biofuels [20], biogas [21], wood-based products [22], natural fibres [23] and more, there have been only very few studies done so far, for bio-based plastics [11, 12, 13]. For this paper, one such study is considered, which is "Life Cycle Assessment of bioethanol-based Polyvinyl Chloride (PVC). Part 2: Consequential approach" by Rodrigo AF Alvarenga.et.al [11]. The study also assesses the effects of indirect land use change (iLUC) caused by sugarcane expansion, which is the feedstock to produce bio-based PVC. Some of the findings from this study are given below:

- Environmental impacts due to iLUC were analyzed in this study through scenario analysis, as bioethanol based PVC
- Marginal production of bioethanol instead of average data for the production of the same was taken for the LCA i.e. it assessed the bioethanol coming exclusively from new places of sugarcane cultivation
- Effects of market development like rebound effect and market mechanisms were not considered
- There are uncertainties with the Life Cycle Inventory (LCI), which were addressed in the interpretation of results, especially with regards to the quantification of iLUC and the uncertainties underlying the methods to calculate them
- Even though the introduction of iLUC did not affect the environmental impact categories, the shift from fossil ethylene to bio ethylene did have significant environmental gains in some impact categories
- The effects of iLUC should be considered when assessing new bio-based products, as some environmental gains may be nullified if there is a low control on deforestation caused by iLUC

The categorization of LCA approaches into attributional and consequential approach was to show that the results from both the approaches could be used to identify the eco-design strategies for the production of bio-based plastics. However, the findings from the ALCA approach for bio-based plastics comes from a review of a number of LCA studies, done for the same. Whereas, there have been only very few CLCA studies for bio-based plastics [11, 12, 13]. Therefore, a comparison/differentiation between the two approaches will be futile. In addition, each of the ALCA and CLCA study has its own goal and system boundaries. The choice to use which LCA approach, system boundary, methodology, type of LCA (screening, comprehensive) and so on lies solely on the producer and he/she needs to justify the decisions before taking these results into the eco-design framework.

2.2. Ecodesign of bio-based plastics

Ecodesign helps the product developers to identify hotspots in the manufacturing of products thereby reducing the environmental impacts and increasing the material and energy efficiency. Eco-design gives a clear understanding about the nature of the product and the processes from technical and sustainability point of view. An eco-design strategy begins with a) An idea for the new product (Brainstorming and feasibility studies to increase recycling, reduce material and energy consumption); b) A conceptual design (Specify type of material to increase recycling, minimal packaging); c) A preliminary design (Details of the product, qualitative estimates of the environmental improvements of the new design); d) A detailed design (Including all the data needed for manufacturing the new product based on the new design that also includes EoL options) [24].

Eco-design of the bio-based plastics is needed now more than ever to make it as a sustainable alternative not only from the feedstock point of view but also from the product point of view. The eco-design and eco-redesign (an associated concept of eco-design, where the current product is reviewed and its design is revised accordingly [25]) strives for the longevity of these products. Eco-design of bio-based plastics can be performed at several levels and this is done based on Mansson [26] and Holmberg.et.al. [27]:

- Raw material (Sourcing of biomass feedstocks)
- Material (Bio-based additives instead of fossil based)
- Component (Recyclable/biodegradable components)
- Subsystem (Usage of drop-in polymers like Bio-PE)
- System (Sourcing of local raw materials)
- Strategic (Improving the properties of the product to compete with the conventional ones)
- Value (Social and cultural aspects)

Based on these different levels, an eco-design plan can be setup in such a way that it fulfills its goals. There have been instances of identifying eco-design strategies based on the results of LCA for some of the (bio) polymers and other bio-based products. These studies are used for the selection of (bio) polymers as well as changing the design of products made of biomass based on environmental and mechanical impacts. For this paper, some of them have been studied and are presented in Table 1 along with its corresponding eco-design levels. Recommendations for integrating the eco-design and LCA results (attributional and consequential) are then drawn from the findings in these studies.

Table 1. Eco-design and LCA of polymers.

Study	Polymer/product	Level
Colwill.et.al (2011) [28]	Packaging (PLA, Bio-PE, Bio-PET)	Strategic (Overview, Framework for a ecodesign tool with case studies)
Ribeiro.et.al (2013) [29]	Polymer (PLA and TPS)	Strategic (Cost model, mechanical properties) and LCA and Material (case study with the analyzed polymers)
Tecchio.P (2015) [30]	Bio-PET	System, Material and Strategic (selection, LCA and scalability)
Bovea.et.al (2014) [31]	PVC, PE, PP (Fossil based)	Material and strategic (Single indicator environmental impacts for eco-design)
Soohyung Lee (2015) [12]	PLA	Material and Strategic (Comparison between PLA and fossil based PET)

Apart from the studies in Table 1, some of the eco-design studies were also considered for this paper to create recommendations, specifically to the bio-based plastics. Also, as one can see from Table 1 that these studies are mostly material specific and most of them did not include use and EoL phases, which are important for the bio-based plastics. In addition, most of these studies discuss about the environmental and chemical properties of the polymers and seldom discuss the physical and recyclability properties of the developed products out of these materials. Therefore, some eco-design studies on the developed components from other bio-based materials were considered [32] and a study that identifies the ecodesign requirements and implementation measures for a product, based on the results of CLCA was considered as well [33], due to the unavailability of studies involving the results of CLCA for an eco-design of a product. Based on the findings from sections 2.1 & 2.2, recommendations and challenges for integrating the results of LCA with the eco-design strategies will be discussed in section 3.

3. Challenges and Recommendations

Based on the findings from the previously conducted LCA and eco-design studies, recommendations for integrating LCA in eco-design for a sustainable production of bio-based plastics have been determined. Although there has not been an eco-design study for bio-based products that included both CLCA and ALCA in its framework till now, this paper brings out a recommendation of performing LCA using both the approaches, starting with CLCA, followed by ALCA. By performing CLCA first, the market mechanisms, policy and the indirect effects (land use change, sourcing and cultivation of biomass) involved in the production of bio-based plastics (current and future scenarios) can be studied by the producers even before implementing those strategies in the production. It can then be followed by the ALCA, which uses the collected average primary and secondary inventory data. As the choice of principle to model the product system depends solely on the producers, these recommendations does not differentiate between the two LCA approaches rather suggest taking both of them into their eco-design framework. These recommendations are subject to change and improved in each eco-design team depending upon the decision context. Some of the recommendations to integrate LCA in the eco-design of bio-based plastics are given below:

- Setting up an eco-design team that includes personnel from different expertise like sustainability, markets, material development
- Continuous engagement with the stakeholders and explaining CLCA and ALCA to them
- Identify the competing bio-based products at the national and international level
- Obtain average (primary from manufacturers, secondary from literature) and marginal data as much as possible
- A thorough cost benefit and market analysis need to be conducted for the product along with the economic and technical feasibility of implementing eco-design strategies
- Sourcing of the raw materials, cultivation of biomass and the complete value chain are to be thoroughly investigated (including direct and indirect elementary flows)

- Perform CLCA before production, for a multi-functional system depending on the market mechanisms and different scenarios, using the marginal data
- The results of the CLCA can be used primarily for internal communication within design process
- Then perform ALCA of the finished product including hotspot analysis to identify the relevance of different processes
- Scenario and sensitivity analyses have to be done for both the LCA approaches thereby addressing the uncertainties in the methodology, inventory data and process parameters
- Transparent communication of ALCA and CLCA results
- Identify and implement strategies based on these results
- Analyse the mechanical properties of the finished products
- Innovative strategies to be implemented, to improve the livability and the re-utilization of the bio-based plastic products (Ergonomic to increase usage, incentives for returning the products to the recyclers, cost optimization based on the biodegradability, collaborations with the local municipalities to handle the wastes)
- Usage of renewable materials need not to be considered as an eco-design measure in the case of bio-based plastics. There have been instances, where it was found out that renewable raw materials does not directly lead to a sustainable production of products [34]
- Collaboration with respective experts is recommended, especially in the case of CLCA of bio-based plastics and market analysis of biopolymers
- The future bio-based plastics should be made of 100% bio-based materials (bio-based additives) as it was studied that the consumers seemed more positive with a fully bio-based product than partial ones [35]
- Technologies and advancements for the bio-based plastics in the future must be considered.

Even though these recommendations are subjective and based on the interactions between different stakeholders, these recommendations when implemented position the bio-based plastics in the global plastics market better than where it is now. However, these recommendations come along with challenges that need to be addressed while integrating the results of LCA with eco-design strategies. Some of these challenges are given below:

- Identifying eco-design strategies can be time intensive
- Not all stakeholders would be ready to engage completely with the eco-design strategies citing reasons such as legal framework, competition, hidden costs
- Costs in performing eco-design (personnel, man-hours, data collection) need to be assessed beforehand and should be included in the budget
- All the members in the team should be well informed in their expertise. One mistake or a faulty analysis could put the production of new products and policymaking into risk
- Eco-design approach is entirely subjective. However, the choice of the methodology should be justified with a scientific and technical background
- Interpretation and communication of the results of ALCA and CLCA of bio-based plastics can be challenging owing to the aspects like methodological choices, land use changes and therefore require clarity in communication
- False interpretation and greenwashing in the interpretation of the strategies and results for bio-based plastics from different stakeholders is possible.
- Difficult to estimate the usage behavior of consumers, future policy amendments on the manufacture and usage of bio-based plastics
- Economic and technical feasibilities in implementing eco-design strategies (selection of cost-intensive technologies, materials) for bio-based plastics can be uncertain
- Estimating future scenarios and technologies for the eco-design of bio-based plastics come with an uncertainty

Some of the above recommendations and challenges may seem to be generic i.e. they can be found in the eco-design framework of commonly used products as well. This has to do with the fact that there has not been a methodology or a framework to perform eco-design for bio-based plastics until now and this paper identifies the need for integrating CLCA and ALCA results with the eco-design of bio-based plastics based on the reviewed studies. However, some of the recommendations specific to the bio-based plastics like the biodegradability, recyclability and most importantly the sourcing of feedstocks have been identified. As the value chain of the bio-based plastics is similar to other bio-based products like biofuel, emphasis have been made on the use and end-of-life phase of the bio-based plastic products.

Eco-design is an iterative approach, which always strives for a continuous feedback before and after implementing the strategies in the product development. The eco-design team should be open-minded and look into the different properties, markets and sustainability aspects of the material used in the production of bio-based plastics, extensively for a better understanding and transparent communication.

4. Conclusion

To make bio-based plastics as a sustainable alternative to the conventional fossil-based plastics, recommendations to integrate eco-design with both the results of attributional and consequential LCA were discussed, based on the findings from the previously conducted LCA and eco-design studies on biopolymers and other bio-based products. Even though these strategies have its own limitations while implementing, they could pave way to improve the product development and result in a sustainable production of bio-based plastics.

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