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Bio-based plastics - A review of environmental, social and economic impact assessments

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ABSTRACT

Bio-based plastics show an evolving market and application range and therefore have become increasingly popular in research and economy. The limitation of fossil resources as well as linked environmental issues have led to the development of an innovative bioeconomy and also triggered the shift from fossil-based plastics to bio-based plastics. The original motivation for this study was to propose a comprehensive approach to calculate the sustainability performance of bio-based plastics on a global scale. To provide a calculative basis, a review on available data from life cycle assessment (LCA), social life cycle assessment (S-LCA) and life cycle costing (LCC) studies on bio-based plastics was carried out and showed limited availability of quantifiable results with regard to the social and economic performance of bio-based plastics. In environmental LCA, with the ISO-family and related documents, a group of harmonized standards and approaches does exist. However, missing practical and consented guidelines hamper the comparability of studies and the exploitability of data - not only within the bio-based plastic sector but also in comparison to the fossil-based counterparts. Therefore, a calculation for the global sustainability performance of bio-based plastics was merely conducted for the environmental impact category global warming potential. Taking the technical substitution potential of fossil-based with bio-based plastics as well as limitations in data availability into account the estimation was performed for a substitution of approximately two-thirds of the global plastic demand. The results show, that bio-based plastics could potentially save 241 to 316 Mio. t of CO_2-eq. annually. Thereby this study gives a first outlook how bio-based plastics could contribute to a sustainable development, making benefits and drawbacks more tangible.

1. Introduction

The concept of bioeconomy aims for a holistic transformation of economy and society. Bioeconomy describes the industrial use of renewable biological resources. This does not only mean substituting fossil resources and reducing emissions but also creating benefits for different stakeholders such as workers, through bioeconomy as a driver for new jobs – “especially at local and regional level, and in rural and coastal areas” and consumers, while avoiding risks for these groups (European Commission, 2010a). Sustainability, covering environmental, economic and social aspects, is a key factor for a successful transformation and has to be considered for all value chains emerging within the context of bioeconomy. Especially, developing innovative bio-based products entails the capability to promote sustainability at an early stage (see e.g. European Commission (2012) or German Federal Ministry of Education and Research (BMBF) (2011)). One building block of such an economy could be plastic based on renewable resources. Plastics play an important role in society with its application in almost all areas of our daily life, from packaging for food, medical and communication technology to technical applications like automobiles. Today, the majority of these plastics are based on fossil

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resources. Against the background of climate change and finite fossil resources, bio-based plastics have been in the focus of research over the past few decades. With an evolving bio-based plastic market and application range, the sustainability of bio-based plastic has come to the fore and is questioned by different stakeholders. To prevent confusion about the term bioplastics as well as bio-based plastics Fig. 1 shows the classification of bio-plastics and which materials exactly are in the scope of this review.

In particular, new types of bioplastics, which were developed in the past 30 years, are of interest today. These so called "New Economy" bioplastics are distinguished from "Old Economy" bio-plastics which indicate anterior materials, that were in use before fossil-based plastics had even developed, and still exist on the market today (e.g., rubber, cellophane, viscose, celluloid, cellulose acetate, linoleum) (IfBB, 2015). Furthermore, "New Economy" bio-plastics are subdivided into two main groups: "Novel bioplastics" on the one hand imply a new chemical structure and specific material properties. Bio-based plastics that merely have a different feedstock but the same chemical structure and properties as an existing fossil plastic and therefore can be managed in the conventional processing and recycling streams without adaptation, are referred to as "Drop-Ins" (VDI, 2015). Please note: biodegradable plastics based on petrochemical resources, which are also included in the novel "New Economy" bioplastics and "Old Economy" bio-plastics are not in the scope of this study. Biodegradability is understood as the inherent ability of a material to decompose under microbiological activity into naturally occurring substances such as carbon dioxide and water (Andrady, 2015).

In 2014, the global production capacities for bio-based plastics made up approximately 1.48 million tonnes with a share of about 70% durable and 30% degradable materials (IfBB, 2015). With a view to regional capacity development, the main production area for bio-based plastics is currently Asia followed by Europe, North America and South America (IfBB, 2015). Although high growth rates are predicted - production capacities quadruplicate over the next 5 years (European Bioplastics, 2015) - the comparison to conventional plastics with a global production of 311 million tonnes in 2014 (PlasticsEurope, 2015) shows, that bio-based plastics are still growing on a small scale. However, the sustainability performance of bio-based plastics has been under critical observance by different stakeholders lately. As cutting edge products are often judged by their sustainability performance, bio-based plastics have to prove that they offer advantages in all sustainability dimensions in order to be considered a feasible alternative to conventional plastics. So far, a couple of studies have reviewed the environmental sustainability of bio-based plastics (Yates and Barlow, 2013; Hottle et al., 2013), mainly with focus on biodegradable polymers. Yet, a

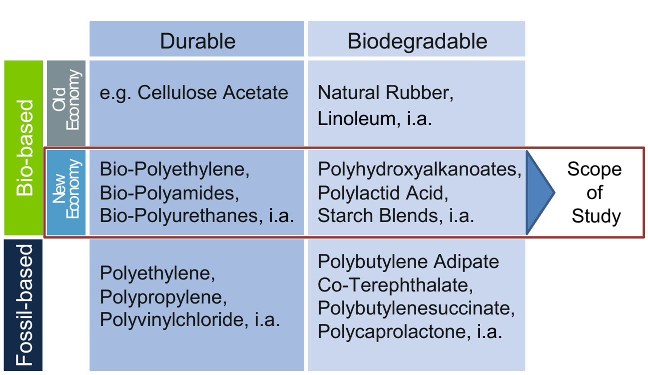

Fig. 1. Framework of bioplastics and bio-based plastics (Figure adapted by authors from Endres and Siebert-Raths, 2011).

comprehensive approach taking all three pillars of sustainability for bio-based plastics into account, has not been conducted until now. It is still an upcoming field of research and there is no real consensus about utilized methods, not only with regards to bio-based plastics.

This study provides an overview on the sustainability assessment of bio-based plastics, presenting the currently common assessment practice and related issues, highlighting methodology gaps. Based on the reviewed studies, an approach is presented on how the sustainability performance of bio-based plastics could be calculated, taking the example of the environmental impact category "Global Warming Potential".

2. Background

The concept of Life Cycle Sustainability Assessment (LCSA) foresees an integrated analysis for each of the three pillars of sustainability, environment, economy, and social aspects (LCSA = LCA + LCC + S-LCA) which was introduced by Klöpffer (2008) and Finkbeiner et al. (2010). Due to the rather specific nature of this approach, it will not be analysed in detail in this paper, the focus will rather be on available studies analysing each of the dimensions. The respective methods for analysing environmental, social and economic aspects are described in the following, with special focus on the characteristics of bio-based plastics.

2.1. Life cycle assessment (LCA)

The assessment of environmental impacts has been in the focus of sustainability assessment within the last decades. Therefore, the internationally accepted standards ISO 14040/44 (ISO 14040:2006 and 14044:2006) have been developed and provide the basic assessment framework. Herein still a wide degree of freedom concerning methodological choices exists. Ongoing differentiations in LCA approaches and emerging new issues have brought up the need for further specifications. For this purpose, the International Reference Life Cycle Data System (ILCD) recommendations (European Commission, 2010b) provide further guidance for the application of LCA. To especially address specific issues that are relevant for biomass-based products, such as allocation of co-products, modelling of land use, water use, and biogenic carbon, the EN 16760 (EN 16760:2015) was recently developed as a supplement to the ISO 14040/44. Although this standard aims to specify bio-material related LCA aspects, most formulations still give no explicit provisions.

A newer approach to enhance the comparability of products regarding their environmental performance is provided by the so called Product Category Rules (PCR) (DIN EN ISO 14025:2011) and Product Environmental Footprint Category Rules (PEFCR) (European Commission, 2013) which aim to determine specified guidelines per product group and to generally foster the application of PCR-based Environmental Product Declarations (EPDs). With UN CPC 347 and Eco Profiles (PCR, 2010; PlasticsEurope, 2011a) two existing PCRs for conventional polymers could be identified. While the PCR "CPC 347- Plastic in primary forms" explicitly includes renewable material-based plastics in its purpose, it lacks giving guidance on relevant issues concerning those feedstocks, such as the treatment of biogenic carbon flows and land use assessment.

Land is an important factor for the production of agricultural goods and is closely linked with direct and indirect environmental impacts on soil, biodiversity, GHG-emissions (greenhouse gas) and water and therefore constitutes a fundamentally relevant impact for bio-materials. Today even simple products can imply a globally distributed land use, which calls for a globally applicable method to assess land use impacts (Koellner et al., 2013). The relevance of this aspect can also be seen in the public food-or-fuel discussion. Due to assessment challenges this impact category currently is still hardly used in LCA (Finkbeiner et al., 2014) but is crucial for the environmental impacts of bio-based plastics. In EN 16760 (2015) land use is treated in a separate chapter but declarations regarding the modelling in life cycle inventory are merely vague and not mandatory. It states that since no scientific consensus on methods for assessment of land use impacts exists, any method can be applied, if properly validated.

The question of whether bio-based plastics are more environmentally friendly than fossil-based ones prominently arises. To answer that question, further alignment of joint frameworks and therein guidance regarding critical issues for the assessment of bio-based plastics is needed in order to enable meaningful comparisons.

2.2. Social life cycle assessment (S-LCA)

The assessment of social aspects with a life cycle perspective (Social Life Cycle Assessment S-LCA) is a rather young field of research compared to the assessment of ecological impacts of value chains via LCA and has been less in focus during the last decades of life cycle sustainability assessment. This can be explained by the perception of ecological aspects to be more urgent on the one hand and by the complexity of social and economic issues and their interdependencies on the other. As an initial step in research a methodological framework on how to assess social aspects within life cycles was presented by Benoît and Mazijn (2009) within the UNEP/SETAC Life Cycle Initiative. The framework was complemented by the methodological sheets (Benoît-Norris et al., 2011) introducing a comprehensive catalogue of indicators connected to a wide set of stakeholders. In 2012 Benoît-Norris et al. (2012) introduced the Social Hotspots Database (SHDB). It was developed in accordance with the UNEP/SETAC guidelines and contains data of indicators for more than 200 countries and 57 sectors. The SHDB is based on an analysis model for global working hours and various social aspects. As a first application of this database pilot, projects were carried out for seven product categories: It is concluded, that the SHDB constitutes an appropriate tool for a top-down approach of possible social influences of the value chain. As weaknesses they name the level of detail of the underlying GTAP (Global Trade Analysis Project) data, the availability and quality of social data and the lack of published research results on social indicators of the various countries and sectors. In further research Benoît-Norris (2013) analyses the availability of data for S-LCA and concludes that, due to growing interest, appropriate data records are increasingly made available. However, there are still major challenges in defining goal and scope of S-LCA and getting in touch with relevant stakeholders.

In recent years several S-LCA studies have been conducted applying the SHDB to different product systems and additional assessment methods were developed. Martínez-Blanco et al. (2014) introduce an application of the S-LCA guidelines within a Life Cycle Sustainability Assessment (LCSA), combined with the integration of the SHDB in a LCA case study on fertilizers. As one outcome the authors state that there is currently no consensus regarding the definition of social objectives for some social aspects in the research community. Furthermore, a comparative S-LCA of concrete and steel as building materials is presented by Housseinijou et al. (2014) who conducted a hotspot analysis on material flow analyses (MFA) and expert interviews using Analytic Hierarchy Process (AHP). In 2015 a database for social indicators for LCA was introduced by Green Delta (2015) called PSILCA. It provides a wide inventory data set for an extensive amount of industries and commodities to assess social impacts along the value chain.

Accompanied by database development, methodical research has been focused on topics such as the characterization of impacts in S-LCA (Dreyer et al., 2010) or on process based approaches such as Life Cycle Working Environment (LCWE) (Knüpffer et al., 2016 in Benoît Norris and Norris, 2016).

2.3. Life cycle costing (LCC)

While LCA has been widely standardized to date within the ISO series (DIN EN ISO 14040:2006 and 14044:2006) and additional guidelines like the ILCD handbook (European Commission, 2010b), LCC lacks generic standardization. Even though conventional LCC is older than LCA, it is standardized only for specific applications like the construction industry (ISO 15686-5:2008), dependability management (DIN EN 60300-3-3:2005) or production (VDI 2884:2005; VDMA 34160:2006). Conventional LCC is especially used to support decision making with regard to invest decisions where the initial investment is substantial and where further monetary flows over the life cycle occur, e.g. costs for energy, maintenance, cleaning or disposal. It is an economic evaluation and widely used approach with focus on net savings, benefits or savings-to-investment ratio (Herrmann, 2010) and lacks compatibility with LCA (Klöpffer, 2008). Therefore, the application of LCC as an integral part of sustainability assessment is still controversial (Jørgensen et al., 2010; Klöpffer and Ciroth, 2011). In case of bio-based plastics, conventional LCC can be of interest especially when it comes to new production equipment.

The concept of environmental LCC (E-LCC) differs from the conventional LCC approach. E-LCC was developed as an economic counterpart to LCA, considering the physical life cycle of a product. In 2008 a UNEP/SETAC working group has developed the LCA-compatible approach of E-LCC and published a book and a respective code of practice (Hunkeler et al., 2008; Swarr et al., 2011a) that aims at providing guidance for performing LCC studies in parallel to LCA. The code of practice (Swarr et al., 2011a) is built on an earlier monograph that summarized 3 years of effort by the SETAC-Europe Working Group on Life-Cycle Costing (Hunkeler et al., 2008). E-LCC takes into account all costs occurring during a product's life cycle regardless of who will incur them. The basis for both economic and environmental assessment is the Life Cycle Inventory (LCI) as the system boundaries are identical, thus ensuring consistency between LCA and E-LCC. The concept of societal LCC (S-LCC) takes this concept one step further, allocating costs, typically borne by society, to products and processes, thus effectively internalizing previously external costs (Swarr et al., 2011b).

Another approach for economic assessment is total cost of ownership (TCO). Similar to LCC, it takes into account not only invest costs but also all costs linked to the use of a product or service (Herrmann, 2010). TCO is typically carried out from the (product) buyer's point of view. In contrast to LCC, TCO also includes transaction costs (e.g. for validation of suppliers or negotiation), thus allowing to compare suppliers (Herrmann, 2010), (Schild, 2005). It is typically applied for services or commodities with lower invest costs, thus making the transaction costs more relevant. LCC is typically used for investment projects since, in that case, transaction costs are typically dominated by purchasing and operating costs and therefore not relevant for decision making (Ellram, 1995).

The review of LCC approaches reveals similarities with S-LCA and allows a distinction to the state of the art of LCA:

It can be stated that, to date, published LCC and S-LCA studies focus on products which are technologically advanced and well established on the market due to data availability and a profound knowledge on production pathways and consumer behaviour towards the product. If a product is under development, companies will be reluctant to publish details on cost drivers and potential revenues in order to not make confidential information available to competitors. Jørgensen et al. (2013) state that LCC provides information that determines whether or not a company will generate benefits with its products and therefore succeed in the long run. It is comprehensible that methods like LCC or S-LCA are applied to established product systems at a first stage. Nevertheless, it can be assumed that conducting social and economic assessments on more immature and innovative products could reveal risks and potentials for improvement and thereby support sustainable product development and policy making to foster the transition towards a bio-economy, as it is the case for LCA during the development process (Lindner et al., 2016). In this context, recent discussions within the research community seem to be promising, as they aim to develop assessment methods, databases and promote further case studies with an increasing awareness on bio-based products (e.g. Benoît Norris and Norris, 2016).

3. Search methodology and scope of the reviewed studies

For the review of environmental, economic and social aspects the literature was searched by using search engines of common publishers (Web of Knowledge, SpringerLink, Elsevier/Sciencedirect and Google Scholar) with focus on sustainability of bioplastics or bio-based plastics respectively. To find studies and reports not published in journals, google search engine was used. The scope of the review focused on studies on life cycle assessment (LCA), social life cycle assessment (S-LCA) and studies on life cycle costing (LCC) of bio-based plastics. Social as well as economic issues are by far less covered in literature than environmental LCA studies. Consequently, the review was extended to social and economic studies on bulk chemicals, bioethanol and biodiesel production, as upstream processes of these product systems can be considered to be comparable to those of bio-based plastics. Further, the evaluation has been extended on reports and case studies beyond the life cycle focus. This research was conducted as additional review of social and economic aspects of bio-based products. As the focus of this paper is on life cycle approaches, no additional assessment methods were investigated. Also labels and certification schemes are out of the scope. The studies under review differ in scope, analysed product systems, assessment methods and indicators evaluated; therefore this paper focuses on the identification of major issues related to sustainability, such as social and economic hotspots, as well as indicators used. For the same reasons a direct comparison of results, as it is presented for LCA results, is not regarded as expedient by the authors. This would require a detailed review of all methods and scopes which would go beyond the scope of this paper. Following search words have been used: Different terms for bio-based plastics including *bioplastics, renewable plastics, green plastics, plastics renewable materials, sustainable plastics* have been combined with terms for the three pillars of sustainability including *S-LCA, social, LCC, economic, LCA, environmental, ecologic*. Additionally following search words have been used for the broadened search for social and economic aspects in the area of bio-based products: *biofuels SLCA*, *bio-based products social LCA*, *social aspects of bio-based products*, *social indicators of biofuels*, *bioethanol social LCA* and *biodiesel social LCA*, *biofuels life cycle costing*, *economic aspects of biofuels*, *economic indicators of biofuels*, respectively.

For the review the focus has been set to gain information on a cradle-to-gate level as the manifold application range for bio-based plastics causes a high variety of use phases. Cradle-to-grave studies have been included as long as cradle-to-gate information for 1 kg of

Table 1
Identified bio-based plastic LCA-studies (cradle-to-gate).

no.	study/source	assessed bio-based plastic									
		Bio-PA	Bio-PBS	Bio-PE	Bio-PET	Bio-PP	Bio-PTT	Bio-PVC	PHA/PHB	PLA	Starch plastic
1	Gerngross and Slater (2000)								x		
2	Kurdikar et al. (2000)								x		
3	Vink et al. (2003)									x	
4	Akiyama et al. (2003)								x		
5	Yokosuka et al. (2004)									x	
6	Bohlmann (2004)									x	
7	Sakai et al. (2004)									x	
8	Kim and Dale (2005)								x		
9	Patel et al. (2006)						x		x	x	
10	Vink et al. (2007)									x	
11	Vidal et al. (2007)									x	
12	Harding et al. (2007)								x		
13	Kim and Dale (2008)								x		
14	Yu and Chen (2008)								x		
15	Vink et al. (2010)									x	
16	Groot and Boren (2010)									x	
17	Kendall (2012)								x		
18	Petchprayul et al. (2012)		x							x	
19	Shen et al. (2012)				x						
20	Chen and Patel (2012)			x	x	x					
21	Novamont (2012)										x
22	Taengwathananukool et al. (2013)									x	
23	Ziem et al. (2013)			x							
24	Alvarenga et al. (2013)							x			
25	Evonik (2013)	x									
26	Papong et al. (2014)									x	
27	Akanum et al. (2014)				x						
28	Tsiropoulos et al. (2015)			x	x						
29	Vink and Davies (2015)									x	

Bio-PA: Bio-Polyamide; Bio-PBS: Bio-polybutylene succinate; Bio-PE: Bio-Polyethylene; Bio-PET: Bio- Polyethylene terephthalate; Bio-PP: Bio-polypropylene; Bio-PTT: Bio-polytrimethylene terephthalate; Bio-PVC: Bio-polyvinyl chloride; PHA/PHB: polyhydroxyalkanoates/polyhydroxybutyrate; PLA: polylactide acid.

Table 2
Most recent bio-based plastic LCA-studies and conventional fossil-based benchmark (cradle-to-gate).

no.	material	source	product system	geographical scope	feedstock
1	Bio-PA[a]	Evonik (2013)	Bio-based plastic	Germany	Castor bean
2a	Bio-PBS	Petchprayul et al. (2012)	Bio-based plastic	Thailand	Sugarcane
2b	Bio-PBS	Chen and Patel (2012)	Bio-based plastic	N/A	N/A
3	Bio-PE	Tsiropoulos et al. (2015)	Bio-based plastic	Brazil	Sugarcane
4	Bio-PET[a]	Tsiropoulos et al. (2015)	Bio-based plastic	Brazil	Sugarcane
5	Bio-PP	Chen and Patel (2012)	Bio-based plastic	N/A	Corn
6	Bio-PTT	Patel et al. (2006)	Bio-based plastic	Europe	Corn, Sugarcane, Ligno-cellulosics
7	Bio-PVC	Alvarenga et al. (2013)	Bio-based plastic	Brazil	Sugarcane
8a	PHA/PHB	Kendall (2012)	Bio-based plastic	USA	Corn, Organic residue
8b	PHA/PHB	Kim and Dale (2008)	Bio-based plastic	USA	Corn
9	PLA	Vink and Davies (2015)	Bio-based plastic	USA	Corn
10	Starch plastic[a]	Novamont (2012)	Bio-based plastic	Italy	N/A
11	PVC, PET, PS,PA, PE,PP	Plastics Europe (2008, 2011b, 2013, 2014a, 2014b, 2014c)	Fossil-based plastic	Europe	Fossil ressources

[a] Partly fossil-based. PA: Polyamide; PE: Polyethylene; PET: Polyethylene terephthalate; PP: polypropylene; PVC: polyvinyl chloride; PS: Polystyrene.

Table 3
Studies on economic aspects of bio-based plastics and bio-based products.

no.	source	Life cycle approach	Product system	Geographical scope
1	Restinanti and Gheewala (2012)	yes	bioethanol	Indonesia
2	Hill et al. (2006)	yes	biofuels	USA
3	Ahouissoussi and Wetzstein (1995)	yes	biodiesel	Denver (Colorado)
4	Luo et al. (2009)	yes	bioethanol	Brazil
5	Grigoletto Duarte et al. (2014)	yes	bioethanol	Brazil

bio-based plastics could have been extracted. While focusing on cradle-to-gate information, it has to be mentioned that the use phase as well as the end-of-life phase can also have a high impact on the overall environmental performance and might even turn around advantages or disadvantages of the cradle-to-gate phase. It is also important to mention that the comparison of different bio-based plastics as well as fossil-based plastics on a cradle-to-gate basis with 1 kg of plastic as reference unit has its limitations due to the different properties each plastic group has. With different plastic products demanding different properties, the amount of plastics needed to fulfill the product property demand might differ from group to group. However, to enhance an environmental comparison on such a level would bring up new challenges e.g. due to the wide range of different products and associated property demands. As quality benchmark for the reviewed data, only either peer reviewed (review process from international scientific journals by colleagues of the scientific community) or critically reviewed (review by life cycle assessment experts in accordance with standards 14040/44 (DIN EN ISO 14040:2006 and 14044:2006) publications were considered.

Within the LCA literature review, 29 suitable studies have been identified which supply primary environmental sustainability cradle-to-gate information on bio-based plastics (compare Table 1).

The main focus of these studies has been on PLA which was investigated in 13 studies, followed by PHA/PHB with nine studies. Other bio-based plastics have only been in the focus of a few studies ranging from four for Bio-PET to one for Bio-PP, starch plastic and Bio-PVC. The four PLA studies (Vink et al. (2003), Vink et al. (2007, 2010) and Vink and Davies (2015)) describe the same product system and represent technological updates of their precursors. Due to process optimizations, with Vink and Davies (2015) representing the latest state of the art value for this product system. However, for the following bio-based plastics no data has been identified: Regenerated Cellulose, Celluloseacetate (CA), Bio-Polyurethane (Bio-PU), Polyethylenfuranoat (PEF). Table 2 shows the most recent publications comparing bio-based and fossil-based plastics, which have been identified for each plastic type. To minimize the impact of methodology developments as well as evolution of characterization factors in impact assessment over the years, the most recent study for each bio-based plastic has been chosen to be reviewed more in detail. These eleven most recent studies have been conducted within the last five years (exemption is Kim and Dale, 2008) and yield information for ten different bio-based plastic types. Also, for Bio-PBS two recent studies were taken into account, because the two latest ones have been published in the same year.

Table 4
Studies on social aspects of bio-based plastics and bio-based products.

no.	source	life cycle approach	product system	geographical scope
1	Álvarez-Chávez et al. (2012)	yes	bio-based plastics	–
2	Ren et al. (2015)	yes	bioethanol	China
3	Manik et al. (2013)	yes	biodiesel	Indonesia
4	German et al. (2011)	no	biofuels	Brazil, Ghana, Indonesia, Malaysia, Mexico, Zambia
5	Grigoletto Duarte et al. (2014)	yes	bioethanol	Brazil
6	Patel et al. (2006)	no	bulk chemicals	European Union
7	Ekener Petersen et al. (2013)	yes	biofuels, fossil fuels	Russia, Norway, Nigeria, Brazil, France, USA, Lithuania
8	OECD (2014)	no	bulk chemicals, bio-based plastics	OECD member states
9	RSB (2014)	no	biofuels	regions of poverty (according to UNDP)

For PHA/PHB the most recent study Kendall (2012) was substituted by the second most recent Kim and Dale (2008). This, due to the fact that the values of Kendall (2012) differ highly from the values of the other PHA studies and the uncertainties of the study are high due to data based on engineering calculations and laboratory-scale data collection.

Due to the relative novelty of Social Life Cycle Assessment the question to be answered by the literature research was less focused on methodical approaches. The same applies for LCC. This is due to the small amount of published LCC studies in the field. The aim for S-LCA and LCC was to identify overlaps in the findings of most relevant socio-economic impacts, to detect hotspots in the value chains of bio-based plastics and the dependencies of impacts and geographical scope. With the search for studies on bio-based plastics assessed with S-LCA approaches, only one study was found (Álvarez-Chávez et al., 2012). In the case of LCC no study was found. A reason might be that producers of bio-based plastics do not publish the outcomes of such studies, as a lot of the information is confidential. Table 3 and Table 4 summarize the scopes and approaches of the literature identified, also including studies on other bio-based products.

The LCC studies reviewed by the authors are mainly built on data provided by governments, interviews and literature. Identified S-LCA studies mainly used data from the Social Hotspot Database (SHDB), interviews, surveys and literature.

The geographical scope of all studies under review is rather wide, covering countries in Africa, Asia, Europe, South and North America. LCC studies mainly focus on the profitability of biofuels and required investments. Similarly, assessed social indicators diverge widely, as shown in Table 5. It provides an overview of all identified studies with social scope and their subsequent indicators matched with the UNEP/SETAC indicator list according to Benoît and Mazijn (2009). Patel et al. (2006), OECD (2014) and RSB (2014) were not compared as they are potentiality studies, guidelines and policy documents and do not contain an impact assessment in the proper sense of the word.

Though the presented S-LCA and LCC studies differ in scope and assessment methods, they can serve as a basis to derive relevant social and economic indicators for bio-based products. As the studies have a large geographical coverage, it can be assumed that the studies provide insight into what is deemed relevant by researchers in a wide range of cultural settings. The following chapters will summarize the main findings and provide estimation on how results can be transferred to sustainability assessments on bio-based plastics.

4. Results

4.1. Life cycle assessment (LCA)

The review of life cycle assessment studies for bio-based plastics identified 29 studies containing information on a cradle-to-gate basis. Table 6 shows an analysis of the identified LCA studies focusing on basic points as well as methodological choices. The overview shows, that the identified studies have a wide range of methodological choices. However, in particular the used impact assessment methods, allocation methods, credits for by-products, the inclusion of biogenic carbon as well as the background of data (industry or R&D data) have an influence on the results (Shibasaki, 2008). While the LCAs for fossil-based plastics show a certain comparability due to existing product category rules like the CPC 347 (PCR, 2010) and EcoProfiles (PlasticsEurope, 2011a), the wide range for bio-based plastics reflects the missing guideline for them. Therefore, the development of a joint guideline or product category rule for fossil-based and bio-based plastics would be needed for a more solid comparison. Although, the current CPC 347 (PCR, 2010) does not explicitly exclude bio-based plastics and even mentions plastics based on renewable material as part of the scope of this product category rule, this current PCR has gaps for bio-based plastics (e.g. handling of biogenic carbon and land use) which should be closed by updating the existing product category rule.

The handling of biogenic carbon is especially important for a comparison of bio-based and fossil plastics on a cradle-to-gate basis. As stated by Pawelzik et al. (2013) it is recommended to include the stored biogenic carbon for this system boundary. As both material types generally contain carbon, that is released at their end-of-life and their production equally causes emissions, the special feature of biomass-based systems is the uptake of short cycle atmospheric carbon through the feedstock, which can be accounted as negative flow in the GHG-emissions profile. This negative flow is neutralized in case of a CO_2 emission in the end of life treatment e.g. as a result of incineration. Since, due to lack of standard guidance, in LCA practice some practitioners consider biomass ex ante as “carbon-neutral”, so that informations about the material carbon content and related CO_2-uptake and emissions are omitted. This lack of information leads to an imbalance when modelling the EoL of both systems in comparison, since the fate of the biogenic carbon can not be modelled, especially if other GHGs than CO_2, such as methane, occur. It has to be mentioned, that sound claims regarding the overall advantages and disadvantages of a product system can only be made considering the whole life cycle.

While three publications chose a basic approach not taking into account specific regional factors, the publication regions of the other studies correspond with the current main production areas for bio-based plastics. In Table 7 the environmental impacts of bio-based plastics and conventional fossil-based plastics are shown for ten different impact categories which have been addressed in the studies. While only four of the ten studies have addressed more than three impact categories, the main focus is on GWP which has been assessed by all studies. For the bio-based plastics the GWP ranges from -0.3–11.9 kg CO_2-eq./kg material. The GWP performance of the fossil-based plastics which is published by PlasticsEurope in accordance to their methodology (PlasticsEurope, 2011a), ranges from 1.6 to 6.4 kg CO_2-eq./kg material and therefore shows a higher minimum value as well as a lower maximum value in comparison to the bio-based plastics. The non-renewable energy use (NREU) for bio-based materials with 1.1–92 MJ/kg material shows mostly lower values than 55.5–155.9 MJ/kg material for conventional plastics. While all LCA studies on conventional plastics indicate values for the NREU, this is only for six out of ten bio-based plastic studies the case. For acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP) the situation is similar. While values are provided by nearly all examined studies on conventional plastics, there is less information on bio-based materials. For example the POCP is declared for merely three bio-based plastics out of ten and varies from 4.0E-13 to 3.2E-04 kg C_2H_4eq/kg material. Other categories such as human toxicity (HT), ecotoxicity (ET) and water consumption (WC) are not covered at all in the LCA studies of conventional plastics and only scarcely for bio-based plastics. The land use, which is an important category for materials derived from biogenic resources, is solely given for PLA and Bio-PTT while all other plastic types lack this information. Also, land use is only assessed in terms of square meters occupied, but no impacts

Table 5
Social issues related to five stakeholder groups according to Benoît and Mazijn (2009) assessed in literature.

source	social issues															
	worker								consumer					local community		
	Freedom of Association and Collective Bargaining	Child Labour	Fair salary	Working hours	Forced labour	Equal opportunities/ discrimination	Health and safety (worker)	Social benefits	Feedback mechanism	End of life responsibility	Health and safety (consumer)	Consumer privacy	Transparency	Access to material resources (local)	Access to immaterial resources (local)	Delocalization and migration
Álvarez-Chávez et al. (2012)							+									
Manik et al. (2013)	+	+	+	+	+	+	+	+					+	+	+	+
German et al. (2011)								+						+		
Grigoletto Duarte et al. (2014)			+	+												
Ekener Petersen et al. (2013) [a]	+	+	+	+	+	+	+	+	+	+	+	+	+			+
Ren et al. (2015)) [b]								+								

[a] The authors name as impacts categories assessed: human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions with limitations in access to material and immaterial resources.
[b] The authors also assess "food security" in the stakeholder group "society" which is assigned to "contribution to economic development" in this Table.

thereof are considered. The GWP is currently the most covered impact category within the environmental assessment of bio-based plastics. The bandwidth of values is mainly caused by different feedstock sources (e.g. sugarcane, corn or by-products) as well as methodological choices (including/excluding biogenic carbon, assuming a life span beyond the scope of the study, thus effectively considering materials as carbon sinks, widely varying end of life assumptions such as allocating burdens for not energetically converting the material or different allocation methods).

4.2. Social life cycle assessment (S-LCA)

The assessment of social aspects of bio-based fuels and chemicals, indicates equally that upstream processes in the agricultural sector have a high social risk potential. This is mainly due to the fact that many raw materials for bio-based products are cultivated in countries with low social standards and weak legal conditions. It has to be noted that S-LCA studies are typically carried out jointly with regular LCA studies. In this paragraph, only the social aspects of those studies are considered. German et al. (2011) reviewed six studies on environmental, social and economic impacts of biofuels in six countries and their implications for governmental policies. They conclude, inter alia, that the fight against poverty, rural development and creation of jobs are the social issues, that are primarily addressed by governments are in order to strengthen local biofuel markets. Tackling these issues requires involving all relevant stakeholders and a balance between environmental and social costs. For example cultural, economic and nutritional aspects are to be considered when transferring the ownership of land. As a key factor the authors identify a need for the protection of customary land rights by law. These aspects are specified by the study on palm oil biodiesel from Indonesia presented by Manik et al. (2013). They identify exploitative working conditions, alienation and negative impacts on liveability and communities as the most decisive indicators within the product assessment. These impacts are intensified by the fact that indigenous groups are the most vulnerable but are forced to bear the mentioned consequences of feedstock production. Grigoletto Duarte et al. (2014) complement this result by pointing out that relevant factors for the local residents are creation of qualified jobs, avoidance of migration and as a consequence, a strengthening of the local community. However, respondents indicate concerns regarding specialization and a shift of jobs from agriculture to industries, but it can also be expected that new jobs might offer an improvement of security and earnings. In addition, small-scale producers are burdened with bearing investment costs to be competitive. The findings described above can similarly be found in Ekener Petersen et al. (2013) who applied the Social Hotspots Database (SHDB) on diesel, petrol, biodiesel and ethanol. This is the only reviewed study that directly compares social impacts of fossil and bio-based fuels. Within a risk assessment they conclude that notable negative impacts occur on the same level for fossil and biofuels. Thereby the country of origin turned-out to be of more importance than the fuel type. The authors deduce from this result that developing sustainability criteria should not only focus on bio-based fuels but also on fossil fuels. Major social concerns like labour issues, human rights and health and safety are identified. A study on sustainability of bioplastics conducted by Álvarez-Chávez et al. (2012) assesses work place related impacts regarding health and safety. They conclude among other results that no bioplastic under commercial use or development is fully sustainable regarding environmental and health and safety impacts. Ren et al. (2015) conducted their study to combine different assessment methods and thereby identify the most sustainable biodiesel production pathway in China within their scope. The study assesses social benefits, contribution to economic development and food security.

As mentioned before, additional documents on social sustainability beyond life cycle perspective and therefore beyond S-LCA were reviewed within this study. These studies of the potentials and guidelines are consulted as they indicate recent and future challenges and opportunities of bio-based products from a governmental point of view. The main global production regions for both biofuels and bio-based plastics are quite similar, being Asia, North and South America and Europe. However, there is a difference in the production output among these regions. It is assumed that each region focuses on the economically more viable product in order to maximize earnings. Most biofuels are being produced in North America (52% market share) and South America (30%); whereas Europe (10%) and Asia (9%) have a rather small market share (Statistica, 2017). For bio-based plastics, main production hubs are Asia (43% market share), followed by Europe (27%), North America (23%) and South America (6%) (European Bioplastics, 2016). It is expected, that the production of bio-based plastics will grow strongly in Asia, with the main growth expected in Thailand, India and China (Greener Package, 2014). It is assumed that the agricultural upstream processes are comparable within each respective country regardless of whether biofuels or bioplastics are produced. It is thus assumed, that the findings of the studies on social aspects of other bio-based products are transferable to bio-based plastics. Therefore they can serve as

social issues														
local community						society					value chain actors (excl. consumers)			
Cultural heritage	Local employ ment	Safe and healthy living conditions (local community)	Respect of indigenous rights	Community engagement	Secure living conditions	Technology development	Public commitments to sustainability issues	Contribution to economic development	Prevention and mitigation of armed conflicts	Corruption	Supplier relationships	Fair competition	Promoting social responsibility	Respect of intellectual property rights
+	+ +	+	+	+		+	+	+		+		+	 +	
+	+	+	+	+	+	+	+	+ +	+	+	+	+	+	+

complementary material for this literature review that aims to assess the state of the art of research on sustainability and social and economic aspects of bio-based plastics. Result indicators addressed in those studies are different from those typically addressed in S-LCA but may provide input on further aspects to be addressed beyond S-LCA.

Patel et al. (2006) assess, inter alia, key factors of public awareness towards white biotechnology for bulk chemicals beyond the life cycle approach. The authors conclude that the main aspects are to reduce greenhouse gas emissions and the use of fossil resources, waste reduction, and contributing to energy self-sufficiency, job creation and ethical aspects.

In the guidelines for rural and social development published by the Roundtable on sustainable Biomaterials (RSB, 2014) recommendations were elaborated on how the situation of local stakeholders in regions of poverty according to the Human Development Index set by the UNDP can be improved. As a result, the focuses amongst others are setting up joint ventures, creating reliable business models, local job creation, gender equality, contract farming, capacity building, social infrastructure, and support by NGOs and government.

In the framework of a policy study on bio-based chemicals and bio-based plastics published by OECD in 2014 an evident high potential for job creation and value added due to bio-based materials production compared to biofuels and bioelectricity is suggested. Based on a European estimate, the authors summarize that “in 2011, there were roughly 150,000 jobs in Europe in each of bio-based materials and biofuels production. However, the turnover from biofuels production was EUR 6 billion, whilst the turnover from bio-based materials, with the same number of jobs, was estimated to be EUR 50 billion, more than eight times higher than for biofuels” (BRIDGE 2020 (2012), cited in OECD 2014).

4.3. Life cycle costing (LCC)

In summary, the LCC studies under review reveal that the competitiveness of biofuels is strongly influenced by the benefit of subsidies (Hill et al., 2006) and the assumed oil prices (Ahouissoussi and Wetzstein, 1995; Luo et al., 2009). Nevertheless, biofuels appear having a better cost benefit ratio if externalities of environmental burdens are considered (Restinanti and Gheewala; 2012). However, LCA on biofuels have a wide range of results, as described in this paper. While it can be concluded that the internalisation of external effects may provide a useful tool for a holistic cost assessment, the underlying data basis obtained from LCA is debatable and should not be accepted without challenging the underlying study. Furthermore, biofuels can profit from environmental and economic advantages of waste recycling and the technological progress expected (Luo et al., 2009). Grigoletto Duarte et al. (2014) who conducted both an economic and social assessment point out that, in the case of Brazil, higher costs for bio-based ethanol occur in connection with investments necessary to meet national employment and environmental law, which causes problems especially for small-scale producers that don't have access to resources and finance to the same extent as large industries. This is a practical disadvantage as the consumer's willingness to pay does not allow covering these costs so they cannot be passed on.

5. Estimation of sustainability performance of bio-based plastics

To quantify the sustainability of bio-based plastics on a global scale, the results of the literature review are set into context with the technical substitution potential for bio-based plastics which was published by Shen et al., in 2009 as well as the global plastic demand. The technical substitution potential describes which fossil-based plastics can be substituted by bio-based plastics due to similar properties. It has been conducted by taking into account the different application areas of fossil-based plastics as well as the specific technical properties needed. The result is a distribution key in percentage. So far, such a broad estimation has only been conducted by Shen et al., (2009), and is based on the technical status from 2009. The substitution percentages of each bio-based plastic type as well as the sum percentages are shown in Table 8. Although Shen et al., 2009 provide the substitution potentials for more fossil-based plastics the estimation has been limited to the main bulk plastics PE, PP, PVC, PS, PET and PUR as only for these plastics valid information on the demand has been available.

Table 9 shows the demand of conventional plastics on a European and global level. The six most commonly used plastics (PE, PP, PVC, PS, PET and PUR) account for 80.2% of the overall demand. The remaining fraction of plastics are summed up in the category “others” and constitute a share of 19.8% including plastics such as ABS and PA.

The following calculation is the basis to estimate the performance of bio-based plastics with respect to the different sustainability indicators (all three pillars) on a global scale:

1) Technical substitution potential in Table 8 is applied to the actual global demand of plastics in Table 9 resulting in:
   a. Countable amounts of theoretically replaceable fossil-based plastics are subdivided by plastic type
   b. Countable amounts of bio-based plastics as substitutes grouped by plastic type
2) Resulting amounts of a. and b. are multiplied with the according indicator values (regarding all three pillar of sustainability) found within the literature review, as far as quantifiable data is available (Table 7)

Table 6
Overview on basic points and methodological choices of the reviewed studies and of bio-based plastics (y = yes, n = no, n.a. = information not available in study).

sources	Criteria																
	Assessed bio-based plastic	Assessment tool	Focused Standard	Geographical scope	Data origin	Functional unit of study	Feedstock	Life Cycle Impact Assessment methodology	System boundaries	Technology status of core process (bio-based plastic production	[%] Biogenic carbon content	Incl. biogenic carbon	Incl. land use change	Carbon sequestration in soil	Multi-functionality	Credits n.c. = no credit	GWP100 per kg (kg CO_2-eq.) *timeframe n.a.
1 Gerngross and Slater (2000)	PLA	n.a.	n.a.	n.a.	Secondary Data	1 kg	Corn	n.a.	cradle-to-gate	n.a.	n.a.	n.a	n.a	n.a	n.a	n.a	n.a
1 Gerngross and Slater (2000)	PHA	n.a.	n.a.	USA	Primary Data	1 kg	Corn	n.a.	cradle-to-gate	n.a.	n.a.	n.a	n.a	n.a.	n.a.	n.a	n.a
2 Kurdikar et al. (2000)	PHA	n.a.	ISO 14041:1998	USA	Secondary Data	1 kg	Corn Stover	IPCC 1998	cradle-to-gate	R&D	n.a.	y	n	n	Mass Allocation/ System expansion	Steam	−3.2/- 4
3 Vink et al. (2003)	PLA	n.a	ISO 14042:2000	USA	Secondary Data	1 kg	Corn/Corn Stover	The Boustead Model	cradle-to-gate	R&D	n.a.	y	n.a.	n.a.	The Boustead Model	n.c./Energy Credit	1.2 to 1.8/-0.3 to -1.7
4 Akiyama et al. (2003)	PHA	SuperPro Designer v4.5	n.a.	USA/Japan	Secondary Data	1 kg	Corn/ Soybean	n.a.	cradle-to-gate	R&D	n.a.	y	n.a.	n.a.	n.a.	Fuel production/n.c.	0.26/0.45
5 Yokosuka et al. (2004)	PLA	GaBi4	n.a.	USA/Japan	n.a.	1 kg	Corn	n.a	cradle-to-grave	n.a	n.a.	y	n.a.	n.a.	Mass Allocation	Energy	5*
6 Bohlmann (2004)	PLA	n.a.	ISO 14000 Series	USA	Secondary Data	1 kg	Corn	n.a.	cradle-to-grave	R&D PLA Production	n.a.	y	n	y	n.a.	carbon sequestration	0.74*
7 Sakai et al. (2004)	PLA	n.a.	n.a.	Japan	Primary Data	1 kg	Foodwaste	n.a.	cradle-to-gate	R&D	n.a.	n.a	n.a.	n.a.	n.a.	n.a.	n.a.
8 Kim and Dale (2005)	PHA	n.a.	ISO 14041:1998	USA	Secondary Data DEAM LCA Database	1 kg	Corn/ Corn + Corn Stover	DAYCENT-Model/ TRACI	cradle-to-gate	R&D	55.8	y	n.a.	x	System Expansion/Mass Allocation	various/n.c.	−1.19 to 1.72/-1.15 to 1.92
9 Patel et al. (2006)	PHA	BREW tool (White Biotechnology Assessment Tool)	ISO 14040:1997 14041:1998 14042:2000 14043:1999	EU	Secondary Data	1000 kg	Corn/Ligno Cellulosics/ Sugarcane	EPS2000	cradle-to-gate	R&D/Industry	n.a.	y	n.a.	n	Allocation (Mass, Price) System Expansion	Energy	−0.7 to 6.9/-2.5 to 6.9/-3.7 to 6.9
9 Patel et al. (2006)	PHB	BREW tool	ISO 14040 - 43	EU	Secondary Data	1000 kg	Corn/Ligno Cellulosics/ Sugarcane	EPS2000	cradle-to-gate	R&D and Industry	n.a.	y	n.a.	n	Allocation (Mass, Price) System Expansion	Energy	0.7/-1 to 3.8/-2.2 to 2.6
9 Patel et al. (2006)	PHBV	BREW tool	ISO 14040 - 43	EU	Secondary Data	1000 kg	Corn	EPS2000	cradle-to-gate	R&D and Industry	n.a.	y	n.a.	n	Allocation (Mass, Price) System Expansion	Energy	5.4
9 Patel et al. (2006)	PLA	BREW tool	ISO 14040 - 43	EU	Secondary Data	1000 kg	Corn/Ligno Cellulosics/ Sugarcane	EPS2000	cradle-to-gate	R&D and Industry	n.a.	y	n.a.	n	Allocation (Mass, Price) System Expansion	Energy	0.4 to 2.4/-0.4 to 1.5/-0.9 to 1
9 Patel et al. (2006)	Bio-PTT	BREW tool	ISO 14040 - 43	EU	Secondary Data	1000 kg	Corn/Ligno Cellulosics	EPS2000	cradle-to-gate	R&D and Industry	n.a.	y	n.a.	n	Allocation (Mass, Price) System Expansion	Energy	1.8 to 2.6/1.4 to 2.6
10 Vink et al. (2007)	PLA	Boustead Model V 5.0.10 (2005)	Boustead: Eco-Profiles (2005)	USA	Primary Data: NatureWorks	1 kg	Corn	The Boustead Model	cradle-to-gate	Current Technology/ + Wind Energy/+ Process optimizations	n.a.	y	n	n	The Boustead Model	CO2 Uptake + Renewable Energy Certificates	2.023/0.27/-0.68
11 Vidal et al. (2007)	PLA	SimaPro (2002)	ISO 14040 -14043	EU	Secondary Data	1 kg	Corn	IPCC 2001	cradle-to-gate	n.a.	59	y	n	n	n.a.	n	1.77
12 Harding et al. (2007)	PHB	SimaPro v7	n.a.	South Africa	Primary/ Secondary Data	1000 kg	Sugarcane	CML2000 v.2.03 Baseline	cradle-to-gate	R&D	n.a.	y	n	n.a.	n.a.	Energy	2.6
13 Kim and Dale (2008)	PHB	n.a.	n.a.	USA	Primary Data/ Ecoinvent	1 kg	Corn	n.a.	cradle-to-gate	Industry	55.8	y	n.a.	n.a.	System expansion/Mass allocation (various)	n.c./Energy	−1.4 to -2.3
14 Yu and Chen (2008)	PHA	SuperPro Designer V4.9	ISO: 14040 1997	USA	Simulated Data	1 kg	Corn – Glucose/ Vegetable Oil/Corn Stover – Black Syrup	IPCC 2001	cradle-to-gate	R&D	n.a.	y	n	n	n.a.	n	0.49/0.25/0.50
15 Vink et al. (2010)	PLA	n.a.	ISO: 14040:2006, 14044:2006	USA	Primary and Secondary Data	1 kg	Corn	n.a.	cradle-to-gate	Industry	n.a.	y	n.a.	n.a.	n.a.	credit for avoided gypsum mining	0.8 to 1.3
16 Groot and Boren (2010)	PLA	n.a.	ISO: 14040:2006, 14044:2006	Thailand	Primary and Secondary Data	1000 kg	Sugarcane	IPCC 2007	cradle-to-gate	Industry	n.a.	y	n	n	system expansion, price allocation	Energy for bagasse	0.502

17 Kendall (2012)	PHA	n.a.	PAS 2050:2008	USA	Secondary Data/ Ecoinvent 2.0 + GaBi Professional	1 kg	Cellulosic fraction of organic residuals from material recovery facilities	IPCC 2007	cradle-to-gate	R&D	n.a.	y	n	n.a.	n.a.	n.a.	4.4 to 10.2
18 Petchprayul et al. (2012)	Bio-PBS	SimaPro 7.0	ISO 14040 series	Thailand	Primary and Secondary Data	1 kg	Sugarcane	CML 2 baseline 2000/Eco-Indicator 95	cradle-to-grave, cradle-to-gate	R&D	n.a.	y	n.a.	n.a.	n.a.	n.a.	5.38
18 Petchprayul et al. (2012)	PLA	SimaPro 7.0	ISO 14040 series	Thailand	Primary and Secondary Data	1 kg	Cassava	CML 2 baseline 2000/Eco-Indicator 95	cradle-to-grave, cradle-to-gate	Industry	n.a.	y	n.a.	n.a.	n.a.	Energy	1.8
19 Shen et al. (2012)	Bio-PET	n.a.	n.a.	USA/Brazil	Secondary Data	1 kg	Corn/ Sugarcane	IPCC 2007 PAS2050:2008	cradle-to-gate, cradle-to-grave (excluded use phase)	n.a.	n.a.	y	n/y	n.a.	n.a.	n.a.	1.36 to 1.65/ 1.03 to 1.47
20 Chen and Patel (2012)	Bio-PE	n.a.	ISO: 14040:2006 14044:2006	Brazil	Secondary Data BREW tool data	1000 kg	Corn/ Sugarcane	n.a.	cradle-to-gate	Industry	n.a.	y	n	y	n.a.	Carbon sequestration	−0.34/-2.05
20 Chen and Patel (2012)	Bio-PET	n.a.	ISO: 14040:2006 14044:2006	n.a.	Secondary Data	1000 kg	Sugarcane/ Corn	n.a.	cradle-to-gate	Industry	n.a.	y	n	y	n.a.	Carbon sequestration	1/1.4
20 Chen and Patel (2012)	Bio-PP	n.a.	ISO: 14040:2006 14044:2006	n.a.	Secondary Data	1000 kg	Corn	n.a.	cradle-to-gate	Industry	n.a.	y	n	y.	n.a.	Carbon sequestration	−0.25
21 Novamont (2012)	Starch plastic	n.a.	ISO: 14025 UN CPC 347 V3.0 2010	Italy	Primary data	1 kg	Corn	CML 2001	cradle-to-gate	Industry	50	n/y	n.a.	n.a.	n.a.	n.a.	1.94/0.87
22 Taengwathananukool et al. (2013)	PLA	n.a.	n.a.	Thailand	Laboratory, Literature, Field survey	86,22g cup	Cassava	CML2 baseline 2000, IPCC 2006	cradle-to-grave	R&D	n.a.	y	n.a.	n.a.	n.a.	n.a.	2.84
23 Ziem et al. (2013)	Bio-PE	n.a.	ISO: 14040/ 44	Brazil/Europe	Primary data	1 kg	Sugarcane	CML 2001, IPCC 2007	cradle to gate	Industry	n.a.	y	y	n.a.	Economic allocation	Energy	−2.15
24 Alvarenga et al. (2013)	Bio-ethanol based PVC (2010)	Simapro 7.3	ISO 14040	Brazil/Europe	Primary data, Secondary Data, Ecoinvent v2.0	1 kg	Sugarcane	Endpoint - ReCiPe, Midpoint - ReCiPe, USEtox, CEENE, IPCC 2007	cradle to gate	Industry	n.a.	y	y	n.a.	Mass allocation in chlorine production and Exergetic allocation in bioethanol production	Chlorine production and energy from Bagasse	−0.0189 to -0.00931
25 Evonik (2013)	PA	GaBi	n.a.	Germany	Primary, GaBi database	1 kg	Castor oil	CML 2000	cradle to gate	Industry	n.a.	n.a.	n	n.a.	n.a.	n.a.	4 to 4.1
26 Papong et al. (2014)	PLA	SimaPro	ISO: 14040/ 44	Thailand	Primary, Secondary Ecoinvent 2008	1000 units of 250 ml drinking water bottles	Cassava	CML2 Baseline 2000	cradle-to-gate	Industry	n.a.	n	n	n.a.	Starch content Allocation	n	2.48
27 Akanuma et al. (2014)	Bio-PET	Simapro v. 7.3.3	ISO: 14044	USA	Secondary Data, Ecoinvent 2.0	1 kg	Corn/Wheat Stover/ Poplar	Impact2002 + v2.1	cradle-to-gate	R&D 3 different production pathways	n.a.	y	n	n.a.	Mass Allocation and Datasets with economic allocation	n.a.	6.81/7.1/4.31
28 Tsiropoulos et al. (2015)	Bio-HDPE	Simapro v 7.3	ISO 14040/ 44: 2006	Brazil	Secondary Data, Ecoinvent 2.2	1 kg	Sugarcane	Impact2002+	cradle-to-gate	Industry	n.a.	y	y	n.a.	System Expansion/ Economic Allocation	n.a.	0.75
28 Tsiropoulos et al. (2015)	Bio-PET	Simapro v 7.3	ISO 14040/ 44: 2006	Brazil/India	Secondary Data, Ecoinvent 2.2	1 kg	Sugarcane	Impact2002+	cradle-to-gate	Industry	n.a.	y	y	n.a.	System expansion, Economic allocation	n.c./Energy bagasse	2.21 to 2.39/ 1.93 to 2.27
29 Vink and Davies (2015)	PLA	GaBi 6.3	ISO 14040/ 44	USA	Primary, Literature, GaBi 6.3 database	1 kg	Corn	CML2001 (04/ 2013)	cradle-to-gate	Industry	n.a.	y	n	n.a.	The Boustead Model	n.a.	0.62

Table 7
Environmental impact of bio-based plastics (most recent values) in comparison with conventional plastics.

Material (1 kg)	Criteria										
	Global Warming Potential (GWP100) [kgCO_2-eq.]	Non Renewable Energy Use (NREU) [MJ]	Acidification Potential (AP) [kg SO2-eq.]	Eutrophication Potential (EP) [kg Po4-eq.]	Photochemical Ozone Creation Potential (POCP) [kg C2H4-eq.]	Ozone Depletion Potential (ODP) [kg CCL3F-eq.]	Human Toxicity (HT) [kg DCB eq.]	Eco Toxicity (ET) [kg DCB eq.]	Land Use (LU) [m^2]	Water Consumption (WC) [m^3]	Sources
Bio-PA[a]	4.0–4.1	–	4.2E-03–7.5E-02	5.2E-03–8.5E-03	3.6E-03–5.5E-03	2.6E-07–3.6E-07	0.6–1.2	–[c]	–	–	Evonik (2013)
Bio-PBS	2.3–5.4	65–92	–	–	–	–	–	–	–	–	Chen and Patel (2012), Petchprayul et al. (2012)
Bio-PE	1.6–2.1	–	–	4.5E-04	–	–	–	–	–	–	Tsiropoulos et al. (2015)
Bio-PET[a]	1.9–2.4	–	–	5.5E-04	–	–	–	–	–	–	Tsiropoulos et al. (2015)
Bio-PP	−3.0E-01	42.0	–	–	–	–	–	–	–	–	Chen and Patel (2012)
Bio-PTT	1.1–2.6	41.8–71.4	–	–	–	–	–	–	0.3–2.0	–	Patel et al. (2006)
Bio-PVC	−9.3E-02–−1.9E-01	13.8–13.4	1.9E-02–1.3E-02	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	Alvarenga et al. (2013)
PHA/PHB	−2,3–−1,4	1,1–6,5	–	–	–	–	–	–	–	–	Kim and Dale (2008)
PLA	6.0E-01	40.1	7.3E-03	1.4E-03	6.0E-04	4.0E-13	–	–	1.5	4.0E-02	Vink and Davies (2015)
Starch plastic[a]	1.9	39.8	8.7E-03	3.1E-03	1.7E-03	3.2E-04	–	–	–	–	Novamont (2012)
PA	6.4	115.9	1.2E-02	4.0E-03	8.0E-04	1.0E-07	–	–	–	–	PlasticsEurope (2014a)
PE	1.8	72	4.3E-03	1.2E-03	9.7E-04	7.3E-07	–	–	–	–	PlasticsEurope (2014b)
PET	2.2	69	7.9E-03	8.1E-04	5.9E-04	1.0E-05	–	–	–	–	PlasticsEurope (2011b)
PP	1.6	70.2	4.3E-03	1.2E-03	3.7E-04	5.5E-07	–	–	–	–	PlasticsEurope (2014c)
PVC	1.9	55.5	6.2E-03	7.1E-04	4.4E-04	–	–	–	–	–	PlasticsEurope (2008)
PUR	4.2	101.5	–	–	–		–	–	–	–	PlasticsEurope (2005)
PS	2.3	82.3	5.5E-03	5.0E-04	8.8E-04	1.7E-08	–	–	–	–	PlasticsEurope (2013)

[a] Partly bio-based.
[b] Available with different unit due to the use of different impact assessment methods.
[c] Available only divided in marine and terrestic ecotoxicity.

Table 8
Global technical substitution potential for bio-based plastics (distribution key) based on Shen et al. (2009).

%Substitution	PE-LD	PE-HD	PP	PVC	PS	PET	PUR
Starch plastics	8	8	8	–	8	–	8
PLA	–	10	10	–	10	20	–
PHA/PHB	20	20	10	10	20	10	10
Cellulose films	–	–	10	10	10	15	–
Bio-PE	72	62	–	–	–	–	–
Bio-PP	–	–	57	–	–	–	–
Bio-PVC	–	–	–	80	–	–	–
Bio-PET	–	–	–	–	–	35	–
Bio-PTT	–	–	5	–	–	20	–
Bio-PUR	–	–	–	–	–	–	80
Sum percentages	100	100	100	100	48	100	98

3) Values of the different plastic types are summed up for a. and b. each and set into ratio.

This estimation should enable an outlook in which category and to what extent bio-based plastics could contribute to a sustainable development, making benefits and drawbacks more tangible. The calculation procedure for the example of GWP and PE-LD is shown in Fig. 2.

Due to the overall limited availability of quantifiable results with regard to the environmental, social, and economic life cycle performance of bio-based plastics the estimation is limited to the GWP in this study. However, even the GWP values could not be calculated for all bio-based plastics identified as potential substitutes due to missing LCA information (Bio-PUR and cellulose films).

Furthermore, data for the plastic demand was merely available for PE, PP, PVC, PS, PET and PUR. Although environmental information have been available for Bio-PBS and Bio-PA it was not possible to include it in the calculation due to missing information on plastic demand. Therefore not all environmental (GWP) information from Table 7 can be used for the calculation of the substitution potential. The estimation covers the substitution of 65.8% (technical substitution potential for the global demand in 2015 reduced by missing data on demand for some fossil-based plastic types and missing environmental information for some bio-based plastic types) of all fossil-based plastics on a global scale and is thereby lower than the technical substitution solely. Fig. 3 shows the impacts related to the global warming potential of the global plastic demand caused by fossil-based plastics and bio-based plastics respectively.

For the fossil-based plastics just average values are shown in the figure as the industry association is just supplying average data. Where available for the bio-based plastics minimum and maximum values are used. Following the proposed approach bio-based plastics would emit 241 to 316 Mio. t less CO_2-eq. per year (substituting 65.8% of all plastics). This calculation shows that bio-based plastics can offer a chance to contribute to climate goals. However, the limitations of this estimation will be discussed in detail in the next chapter.

6. Discussion

6.1. Reviewed literature and methodology

Although LCA studies are not available for all bio-based plastics, including types which are still on research and development level and not yet in commercial application, the overview gives an outlook on the potential environmental performance of bio-based plastics. The feedstocks considered in the studies have mainly been 1st generation feedstocks such as corn or sugarcane. Future 2nd generation feedstocks like cellulosic by-products are not in the focus of most studies. A closer look at the assessed impact categories shows that the majority of the studies focus on GWP (see Table 7). Impact assessments, covering more than five impact categories are only given by three of the latest studies on bio-based plastics (Evonik; 2013; Vink and Davies, 2015; Novamont, 2012). While the GWP has been in the focus of most studies due to the challenges connected to climate change, it is also important to take other impact categories into account to enable a more holistic environmental assessment. This would help to prevent burden shifting and support the development of truly environmental beneficial materials. Comparing the identified impacts for the bio-based plastics in context to fossil-based plastics shows mixed results. As the baseline for comparison is 1 kg of material, a direct comparison of novel bio-based plastics to fossil-based plastics only has limited validity due to their unique characteristics (e.g. PLA). For "drop-in" bio-based plastics, like Bio-PE such a comparison is valid based on identical properties. But also for this comparison the results for GWP of Bio-PE (Tsiropoulos et al., 2015) offer a bandwidth of results being either advantageous or disadvantageous, depending on the use of either the lower or the upper GWP value when comparing it to PE (PlasticsEurope, 2014b). The same conclusion can also be transferred to the other impact categories, highlighting that general claims (on a cradle-to-gate-basis) such as a better overall environmental or GWP performance of bio-based plastics compared to fossil-based plastics can not be legitimately based on the studies which have been analysed. However, bio-based plastics such as Bio-PET or Bio-PP show environmental advantages which has to be further analysed with high quality and comprehensive life cycle assessments along all impact categories as well as life stages (also taking use phase and end-of-life phase into account). Such an assessment also has to be based on a robust methodology which adequately addresses relevant aspects for the assessment of bio-based plastics. Product group specific guidelines are a step towards increasing the comparability of environmental impacts of different products or materials, by setting a uniform scope of assessment for the object group. While two PCRs for polymer resins do exist, only one of them directly states its validity for "plastics from renewable resources" (PCR, 2010), nevertheless failing to address those aspects that are crucial for the assessment of bio-based polymers. As the environmental performance of bio-based plastics will always be directly compared to that of fossil-based plastics, an exhaustive common PCR for the different sourced polymers could enhance the comparison issue. While this analysis of the environmental aspects has been focused on the cradle-to-gate values, as

Table 9
European and global demand of plastics based on PlasticsEurope (2015).

Plastic demand (Miot)	PE-LD	PE-HD	PP	PVC	PS	PET	PUR	Others[b]	Sum
Europe	8.1	5.6	8.5	4.8	3.3	3.2	3.4	9.1	46
World[a]	52.3	36.2	55.3	31.1	21.1	20.6	22.1	58.9	297.6

[a] Based on European consumption share.
[b] Inlcuding crylonitrile-butadiene-styrene (ABS), epoxy resins etc.

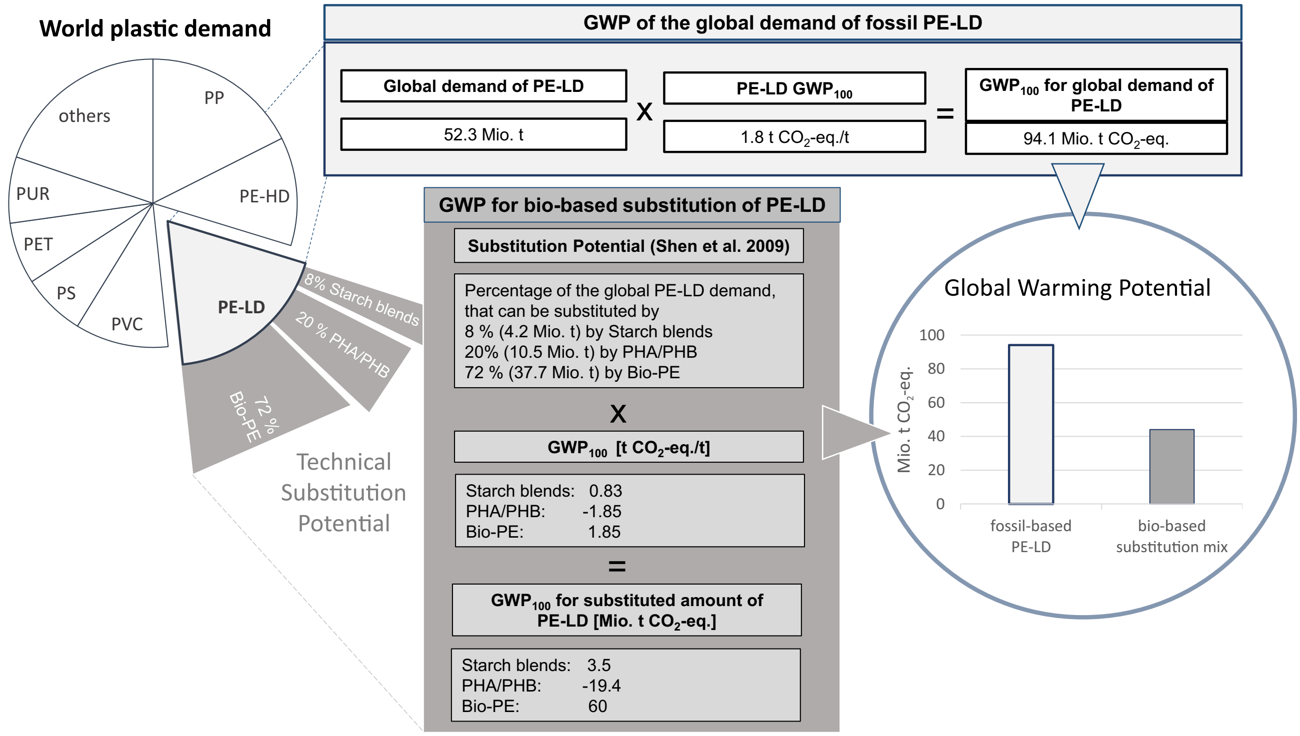

Fig. 2. Calculation procedure for the global sustainability performance of bio-based plastics – example of GWP for PE-LD substituted by starch blends, PHA and Bio-PE.

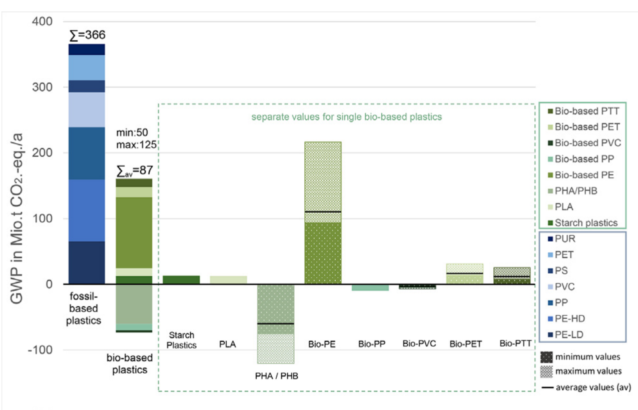

Fig. 3. Global warming potential of fossil-based and bio-based plastics for 65.8% of the global plastic demand.

mentioned before, the use phase and end-of-life phase can also have a high impact depending on product type and waste management. Due to the manifold application ranges, an aggregated approach based on average use and end-of-life values for the existing market segments of bio-based plastics (e.g. flexible packaging, rigid packaging or textiles) might be a promising approach to quantify also the other life cycle phases.

Only few LCC and S-LCA studies on bio-based plastics are published to date (see Tables 3 and 4). To gain an overview on economic and social sustainability literature, comparable bio-based product systems have to be assessed. The comparability of the presented studies is limited due to different products being assessed and a large bandwidth of geographical scopes, differing methods and databases, and especially in the case of S-LCA a great variation in indicators and stakeholder groups considered (see Table 5). It can be stated, that all S-LCA studies assess impacts related to the stakeholder group "worker" while "consumers" and "society" seem to be less in focus. This can indicate that authors expect social hotspots mainly to occur in agricultural upstream processes of bio-based products. Furthermore, it can be assumed that data for indicators for groups like consumers are more difficult to collect, whilst generic data on labour issues are publicly available.

Despite the variation of the studies, overlaps in results can be identified and allow to derive social and economic hotspots of bio-based value chains. Due to the global range of these chains, cultural and country specific conditions have to be taken into account, if a sustainable production is strived for. Especially for rural regions opportunities can arise. Job creation and a value added that remains in the area can strengthen welfare and social security and therewith allow workers to stay within their community and prevent migration processes and alienation. To establish these opportunities successfully and sustainably, legal frameworks and contracts have to be reliable over the long term. A well-managed supply chain in this sense can support a positive attitude of consumers towards bio-based products and herewith strengthen their market position. Further subsidies can simplify research and innovation and consequently allow a successful market entry. The transferability of these outcomes on bio-based plastics can be assumed as agricultural upstream processes are comparable to the ones of biofuels and bulk chemicals.

Research gaps and therewith the lack of reliable results in the field of social and economic sustainability of bio-based plastics is mainly due to the small number of published studies. This can be related to the fact that S-LCA is a comparably new assessment method, while LCC is often used for internal purposes by companies but not often published. Main obstacles are data gaps and approaches for the calculation of qualitative indicators. Further, the lack of standardization hampers the comparability of studies. In addition bio-based plastics as new and innovative products seem not yet to be in the focus of social and economic life cycle based assessments. Nevertheless, it can be expected that research in this field will follow the already advanced environmental assessment of bio-based plastics.

6.2. Estimation of sustainability performance of bio-based plastics

To identify the role bio-based plastics could potentially have in a bioeconomy, it is important to determine the sustainability of bio-based plastics on a global scale. This could serve as a basis to guide future technology developments of bio-based plastics to the most sustainable path. Unfortunately, due to information gaps such an estimation of sustainability performance on a global scale is not possible. Performance values could only be calculated for GWP as part of the environmental sustainability. The estimation shows that bio-based plastics could save 241 to 316 Mio. t. CO_2-eq. per year by substituting 65.8% of all conventional plastics. But even for the GWP the estimation implies many limitations. These limitations include the already mentioned critical methodological aspects, missing information for some bio-based plastic types as well as missing information on plastic demand of some fossil-based plastics and question marks behind the validity of a direct comparison of bio-based and fossil-based results due to a missing joint product category rule. It is also important to highlight, that the environmental information for fossil-based plastics were just available as average industry data. Nevertheless, approaches which indicate the possible overall potential of bio-based plastics are important to examine their capability for a sustainable development as well as an innovative bioeconomy. Furthermore, it supports for a sustainability oriented development of bio-based plastics, highlighting that all aspects have to be considered in order to create a truly sustainable product. However, the qualitatively assessed impacts in the environmental, social and economic area also give an outlook for a positive contribution. Based on the GWP estimation, calculations for other impact categories should be considered, once sufficient data is available. Also the technical substitution potential (from 2009) currently used for the estimation should be updated as the technical development especially in the bio-based plastic sector is dynamic.

7. Conclusions and outlook

Whether bio-based plastics are more sustainable than fossil-based ones, and what contribution they could have as a building block for a sustainable development of an innovative bioeconomy can not be answered conclusively in the framework of this examination due to insufficient data. Nevertheless, the conclusion to be drawn is twofold. First, it becomes obvious that sustainability assessment of bio-based plastics based on Life Cycle Assessment, be it with an environmental, economic or social focus, show a big bandwidth regarding methods, indicators and results. However, based on the literature review so far it is only possible to compare one impact category (GWP) within the environmental pillar and this only with restrictions. Second, results of the review indicate a potential for bio-based plastics in all three pillars of sustainability. To develop these advantages in a sustainable way, all three pillars of sustainability have to be balanced and specific needs of vulnerable stakeholders involved in production processes have to be considered and protected. In this context, support by governments and NGOs is essential in terms of subsidies and legal certainty. Further research on an improvement and harmonization of methodology as well as provision of sustainability information on bio-based plastics is needed to evaluate the real overall potential of bio-based plastics in all its facets.

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