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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Comparing the incomparable? A review of methodical aspects in the sustainability assessment of wood in vehicles

Claudia Mair-Bauernfeind[1] · Martina Zimek[1] · Miriam Lettner[2] · Franziska Hesser[3] · Rupert J. Baumgartner[1,4] · Tobias Stern[1]

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Abstract

Purpose The choice of materials used for a vehicle can contribute to reduce negative environmental and social impacts. Bio-based materials are considered a promising solution; however, the sustainability effects still need to be assessed. Depending on the material assessed, it is questionable which environmental and social impact categories or subcategories should be included since recommendations in guidelines are vague and case studies in this regard are limited. Therefore, this study aims to shed light on the choice of impact categories, methods, and indicators for E-LCA and S-LCA when assessing wood as substitute for conventional materials in automotive applications.

Method The research is based on a literature review covering 115 case studies of S-LCAs and E-LCAs focusing either on wood-based products or on components in automotive applications. The selected case studies were analyzed according to the following criteria: considered stakeholder groups and chosen subcategories (S-LCA sample), sector or product system (S-LCA sample), year of publication and geographical scope (S-LCA and E-LCA sample), chosen LCIA method(s) and impact categories, objective(s) of the studies, analyzed materials and used software support (E-LCA samples).

Results and discussion For S-LCA some relevant social topics for bio-based product systems, like food security or land- and worker-related concerns, could be identified. The E-LCA literature suggests that the objective and material type determine calculation approaches and impact category choices. Some material-related environmental issues like biodiversity loss in the case of bio-based product systems or ecotoxicity for steel and toxicity in the case of aluminum could be identified. For S-LCA the geographical and sectorial context and the affected stakeholders are the determining factors for methodical choices, however, the results show almost no difference in subcategory choice and geographical context. Influencing factors for methodical choices in E-LCA might be the objective of the study, data availability, the up-to-dateness of the LCIA approach, the geographical scope of the study, the materials analyzed, and the availability of software support.

Conclusion Some relevant environmental and social impact categories as well as influencing factors on methodical choices could be identified from existing literature. However, a clear picture on these issues could not be drawn. Further research is needed on the motivation of researches on certain methodical choices as well as on environmental issues connected with materials or geographical-related social topics.

Keywords E-LCA · S-LCA · Wood · Automotive · Impact category · Subcategory

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✉ Claudia Mair-Bauernfeind
claudia.mair@uni-graz.at

1 Institute of Systems Sciences, Innovation and Sustainability Research, University of Graz, Merangasse 18, 8010 Graz, Austria

2 University of Applied Sciences Kufstein Tyrol, Andreas-Hofer-Straße 7, 6330 Kufstein, Austria

3 Wood K Plus, Competence Center for Wood Composites and Wood Chemistry, Kompetenzzentrum Holz GmbH, Altenberger Straße 69, 4040 Linz, Austria

4 Christian-Doppler-Laboratory for Sustainable Product Management enabling a Circular Economy, Merangasse 18, 8010 Graz, Austria

1 Introduction

The automotive industry is confronted with increasing environmental and social requirements. Those challenges are posed by growing social and environmental awareness in the society and the recognition that sustainability is one driver for innovation (Ribeiro et al. 2007). Weight reduction through lightweight design has become an important lever in the automotive industry to decrease use-phase emissions (Delogu et al. 2017). Hence, the choice of materials used for a vehicle can contribute to reduce negative environmental and social impacts. Bio-based materials are considered a promising solution, because depending on the component and the system under study, using wood as a substitute for other materials has the potential to reduce the environmental impacts (e.g., less energy intensive than metals and plastics or less embodied impacts for acidification, climate change, and eutrophication) (Cordella and Hidalgo 2016; Petersen and Solberg 2005; Spitzley et al. 2006). Additionally, wood-based product systems are expected to contribute to social benefits, like an increase in local/rural employment and an improvement of infrastructure (Siebert et al. 2018b). Additionally, Touceda et al. (2018) mention that a substitution with wood can lead to improvements in supply chains like reducing the risk of injuries and fatalities.

The first vehicles were entirely made out of wood like the 1909 Ford Model T (Brooke 2008). Today, a typical passenger vehicle is composed of many materials, but wood is usually not part of a vehicle anymore (Mayyas et al. 2012a; Omar 2011). In recent years, the idea of bringing wood-based materials back into automotive applications has gained some attention again and was studied by several research projects (e.g., HAMMER or WoodC.A.R.[1]) focusing mostly on the technical feasibility but also on potential environmental and social impacts of material substitution or tradeoffs such as the opportunity of regional job creation at the cost of increasing risk of forced labor or increasing GHG emissions (Asada et al. 2020). Accepted methods to assess the potential environmental and social impacts are Environmental Life Cycle Assessment (E-LCA) or Social Life Cycle Assessment (S-LCA) (Benoît et al. 2010; Finnveden et al. 2009; Kloepffer 2008).

S-LCA aims to assess the potential positive and negative social and socioeconomic impacts of products along their life cycle (Dreyer et al. 2010a; Garrido 2017; UNEP/SETAC 2009). One of the most crucial steps in S-LCA is the selection of relevant indicators and impact categories. Impact categories and subcategories are different topics, which are of social relevance and *"are the basis of a S-LCA assessment because they are the items on which justification of inclusion or exclusion needs to be provided"* (UNEP/SETAC 2009, p. 44). When deciding for impact categories, a prioritization of the most relevant categories is challenging due to a lack of previous experience and knowledge (UNEP/SETAC 2009). Although there is a growing interest in S-LCAs in general and in S-LCAs for bio-based product systems, there are few recommendations available on how to decide for impact categories and relevant indicators for assessing bio-based product systems (Hasenheit et al. 2016; Rafiaani et al. 2018; Siebert et al. 2018a; Touceda et al. 2018). The lack of S-LCAs of the respective areas as well as the fact that those are still in its infancy (Petti et al. 2018) makes the identification of relevant social aspects challenging. Some guidance on S-LCA is provided by the UNEP/SETAC guidelines, where a general framework for conducting a study is proposed (Chen and Holden 2017; UNEP/SETAC 2009).

E-LCA aims to assess the environmental impacts of products and services along their life cycle from cradle to grave (ISO 2006a). As it is the case in S-LCA, E-LCA also requires as a first step the definition of the system under study. One aspect hereby is to identify which environmental issues (EC 2010c; ISO 2006a) and respectively which social topics and indicators (UNEP/SETAC 2009) are relevant for the system and should be covered in the analysis. In E-LCA the number and variety of indicators and LCIA methods available makes it difficult to choose the appropriate ones for a certain system under study (Finnveden et al. 2009; Rosenbaum et al. 2018). Understanding the main characteristics of a method and indicator as well as staying up-to-date with the developments in LCIA can be complex and time-consuming (Rosenbaum et al. 2018). Nevertheless, the choice of a LCIA method can be decisive for the outcome of the study, as well as calculating one impact category with different LCIA methods can lead to different results (Dreyer et al. 2003; Höglmeier et al. 2016; Owsianiak et al. 2014; Pizzol et al. 2011). The ISO standards 14040/14044 (2006a, 2006b) recommend to apply internationally accepted models and factors; however, Hauschild et al. (2013) state that none of the existing LCIA methods are accepted like the ISO standards call for. Because every system under study is unique, the recommendations from the ILCD handbook (EC 2010c) or the ISO standard 14040/14044 (ISO 2006a; 2006b) regarding indicators or methods are vague, which leads to rather loose guidance for LCA practitioners. One common recommendation is to include all main relevant environmental issues related to the system under study (EC 2010c; ISO 2006a) without giving criteria for how to rate the relevancy. In the ISO 14044 (2006b), it is stated that the choice of impact categories, category indicators, and characterization models should be consistent with the goal and scope of the study. Additionally, the choice depends on the environmental issues to be covered, the geographical context of the study (including mid- or endpoint assessment), and the interpretability and

[1] HAMMER (http://www.projekt-hammer.de/) and WoodC.A.R. (www.woodcar.eu)

documentation as well as the up-to-dateness of the method (Rosenbaum et al. 2018).

Besides the recommendations provided by the UNEP/SETAC guidelines (2009) for S-LCA and the ISO standards (2006a, 2006b) or the ILCD handbook (EC 2010b) for E-LCA, inputs on relevant social as well as environmental issues can be identified by referring to previous literature with similar research focus (Höglmeier et al. 2016). Unfortunately, just a limited number of E-LCA and S-LCA case studies for wood in automotive applications are available. Just a single study was found assessing the environmental impacts of an engineered wood product in an automotive application (Kohl et al. 2016). However, the authors did not consider the whole life cycle of the component compared with a functional equivalent nor the social effects of the component. No S-LCA case study of wood-based components in the automotive industry is currently available.

Therefore, the aim of this study is to shed light on the choice of impact categories, methods, and indicators for E-LCA and S-LCA when assessing wood as substitute for conventional materials in automotive applications. More precisely the aim is to answer the following research questions. RQ 1: Which environmental and social impact categories or subcategories are considered as relevant when assessing wood as a substitute for steel, aluminum, or composites in automotive applications? RQ 2: Which factors shape methodical choices (e.g., methods or indicators) in environmental and social LCA?

2 Method and material

In order to identify potential social topics and environmental issues as well as influencing factors for the choice of indicators, impact categories, and methods, an analytical approach is proposed by using a literature review. A research literature review can be defined as *"a systematic, explicit, and reproducible method for identifying, evaluating, synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners"* (Fink 2020, p. 6). Literature reviews usually reprocess the current state of research by aiming to provide a summary of themes and issues in a specific field or to identify the theoretical content within the analyzed research field (Engert et al. 2016; Meredith 1993). The approach applied for the present thesis is an interpretative content analysis, which, according to Neuendorf (2017), involves the theoretical sampling, the definition of analytical categories, the cumulative and comparative analysis of literature, as well as the formulation of types or conceptual categories.

To collect relevant E-LCA and S-LCA case studies for answering the research questions , a literature search was performed using the Scopus database, which comprises an adequate amount of scientific papers and journals (Klein et al. 2015). The examined study period was between 1990 and July 2018. The starting year of 1990 for the present study is adequate since the E-LCA literature started to emerge at this time (Zimek et al. 2019) and S-LCA later than the E-LCA literature. To identify the most relevant case studies, the literature research was limited to peer-reviewed articles and primary studies in English. Gray literature was excluded, as mentioned by Petti et al. (2018) within gray literature, a quality control is difficult and a higher quality is given in peer-reviewed studies. In the case of S-LCA, only a limited number of case studies focusing on bio-based product systems, wood-based products, or on components in automotive applications are available. However, the sector or industry specific as well as the geographical context is very important in S-LCA, as — dependent on the product system — there can be important differences within one sector in a country (Dreyer et al. 2006; Jørgensen 2013; Siebert et al. 2018a; Siebert et al. 2018b). Consequently, other case studies besides studies focusing on wood-based and automotive product systems can provide important insights on sector as well as geographic dependent indicators. Therefore, the scope of literature was broadened to include all S-LCA case studies available on Scopus. To collect all those case studies, essential descriptors (keywords) of the examined subjects were chosen: "S-LCA" or "SLCA" or "Social Life Cycle Assessment" or "Social Life Cycle Analysis" and "case study" (present in Article title, Abstract, Keywords). In total 104 S-LCA case studies were identified. However, in this study, publications were analyzed specifically in which a geographical context and sector or product system was indicated since this is seen as essential in S-LCA (Dreyer et al. 2006; Jørgensen 2013; Siebert et al. 2018a; Siebert et al. 2018b). The UNEP/SETAC (2009) provide the general framework for conducting a S-LCA; wherefore, only those case studies are included, in which one or more of the 31 subcategories of the UNEP/SETAC guideline are included, or the chosen impact categories were assignable to the 31 subcategories of the UNEP/SETAC guideline (e.g., "job creation" is assignable to "local employment"). This resulted in 50 case studies for further analysis (see Fig. 1).

Again, just a limited number of E-LCAs with the particular focus of wood for automotive applications are available. However, studies focusing either on assessing wood-based products or on components in automotive applications can provide important insights on the considered environmental issues and impact categories, the chosen LCIA approach, as well as to identify possible methodological differences when assessing the environmental performance of different materials (bio-based and non-bio-based). Therefore, two different

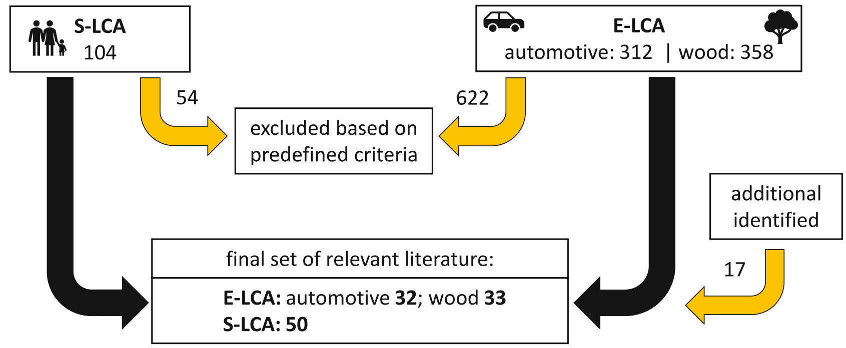


Fig. 1 Identified number of relevant case studies

sets of literature were analyzed: E-LCAs of materials and components in automotive applications and E-LCAs of wood-based products. To identify relevant case studies focusing on assessing wood products, the keywords "Life Cycle Assessment" or "LCA" and "wood" and "product" or "component" or "part" (358) were used for the search. In the case of E-LCAs focusing on automotive components, the search string "Life Cycle Assessment" or "LCA" and "automotive" or "car" or "automobile" was applied which resulted in over 1000 publications. Many of those publications were out of scope and focused on, e.g., unmanned aerial vehicles, spacecrafts, underwater vehicles, planetary robotic rovers or rail, or air vehicles. After trying several additional keywords to limit the results to the most relevant for the present study, the following were found to be the most sufficient: "component" or "material" or "part" or "light*weight" (312). Hereby, those studies that actually focused on components in automotive vehicles and not on the complete vehicle as well as on material substitution effects were identified. The keyword "light*-weight" was included because after screening through the titles after the first search, it became clear that one motivation for carrying out LCAs focusing on effects of material substitution was to identify sustainable lightweight solutions for the automotive industry.

In total this search resulted in 670 studies (Fig. 1) were several studies are still out of the scope for the present literature review. Therefore, the sample was limited according to the following criteria:

- Where a comparative E-LCA case study was performed
- Where the LCIA methods and/or impact categories were explained
- Where the focus of the case study was on assessing the impacts of *solid wood* or *engineered wood products* or *wood-based products/materials* and not on *biofuel* or *construction*
- Where the focus of the case study was on assessing the impacts of components or materials for automotive applications
- Where the focus was on assessing scenarios in order to identify potential benefits of lightweighting

After limiting the number of publications according to the previous listed criteria, a snowballing approach was used to identify additional relevant case studies. Using a snowballing approach means to screen the reference list of a paper or citations to the paper to gather additional relevant literature (Wohlin 2014). In the present study, the references of the papers included in the intermediate literature sample were screened in order to identify additional relevant E-LCA case studies (eight automotive and nine wood LCAs were added to the sample) (Fig. 1).

A qualitative content analysis as described by Neuendorf (2017) of the identified sample was performed by using the software MAXQDA (VERBI GmbH 2019). This method has been chosen as a huge amount of texts can be analyzed in a systematic way. Also, the method is not limited to any specific discipline and supports the researcher in interpreting the content of texts through a coding process (Hsieh and Shannon 2005; Mayring 2000). This was done to identify the factors influencing the choice of indicators as well as subcategories in S-LCA and respectively LCIA methods and impact categories in E-LCA (RQ2). The software was used to code each publication according to the following criteria: considered stakeholder groups and chosen subcategories (S-LCA sample), sector or product system (S-LCA sample), year of publication and geographical scope (S-LCA and E-LCA sample), chosen LCIA method(s) and impact categories, objective(s) of the studies, analyzed materials and used software support (E-LCA samples). The coded text was then analyzed step by step for each criterion to gain relevant information to answer the research questions. In the following chapters, the results of the literature and content analysis are presented. The results are spilt into two sections, one for S-LCA and the second for E-LCA. In each section, a brief insight into the respective method is provided, followed by the results on the relevant environmental and social impact categories or subcategories (RQ1). The last subchapter in the two sections presents the results regarding the influencing factors shaping the choice of methods and indicators in S-LCA and E-LCA (RQ2).

3 Results

3.1 Social life cycle assessment

The UNEP/SETAC guidelines provide a general framework for conducting a S-LCA, where 31 subcategories are being suggested as the basis of a S-LCA (Chen and Holden 2017; UNEP/SETAC 2009). These subcategories are classified into five stakeholder groups (workers, local community, society, consumers, and value chain actors) and impact categories (UNEP/SETAC 2009) (Fig. 2). Although the UNEP/SETAC provide a general framework for conduction an S-LCA, several authors point out that S-LCA is still under development, faces several (methodological) challenges, and lacks empirical studies (Arcese et al. 2018; Baumann et al. 2013; Benoît et al. 2010; Kühnen and Hahn 2017; Salazar et al. 2012; Sureau et al. 2018).

The product or sector/industry and company-specific social impacts highly influence different stakeholders and stakeholder groups (Dreyer et al. 2006). Especially workers and labor conditions gained increasing interest in the S-LCA literature. Labor rights was the focus of Dreyer et al. (2010a), and within their so-called contextual risk classes (CRC), they assessed child labor, forced labor, discrimination, and restrictions of freedom of association (Dreyer et al. 2010b). Additionally, the geographical context and the industry of the companies along the whole supply chain are important since, for instance, the social impacts of an ore mine in Brazil might be completely different compared with the impacts of a sawmill in Austria (Benoît et al. 2010; Dreyer et al. 2010a; Jørgensen 2013).

3.1.1 Social issues for automotive and bio-based product systems

While there is currently no S-LCA case study of wood components in the automotive industry available, there are some studies available that deal with social impacts in the automotive industry (Traverso et al. 2018; Zimmer et al. 2017) or of wood-based products (Siebert et al. 2018a; Siebert et al. 2018b; Touceda et al. 2018) or the social impacts of the bioeconomy (Hasenheit et al. 2016; Rafiaani et al. 2018). A bioeconomy is seen as an economy where the basic components of materials, chemicals, and energy are made out of bio-based resources (McCormick and Kautto 2013). This means a bioeconomy focuses on bio-based products and bio-based product systems; wherefore, the studies of Hasenheit et al. (2016) and Rafiaani et al. (2018) are considered as relevant in identifying social issues of bio-based product systems.

Regarding the social issues of automotive product systems, Zimmer et al. (2017) assessed the social risks of global supply chains and demonstrated different options of analysis for a case of a premium car manufacturer. They point out that not only the choice of the right indicators but also the weighting of indicators (e.g., together with different stakeholders) is of great importance for assessing social risks in supply chains (Zimmer et al. 2017). Traverso et al. (2018) identified 26 relevant indicators to assess the social impacts of a run on flat tire mounted on a BMW3 series. These indicators (e.g., health and safety, wages and social benefits, working hours, child labor, forced labor for workers; no details on the stakeholder groups *other value chain actors* and *society*) are split into

Worker	Other value chain actors
• Freedom of association and collective bargaining • Child labor • Fair salary • Working hours • Forced labor • Equality/ discrimination • Health and safety • Social benefits and social security	• Respect for intellectual property rights • Promoting corporate social responsibility • Healthy competition • Suppliers relations • End-of-life • Feedback mechanism
Local Community	
• Access to material resources • Access to immaterial resources • Delocalization and migration • Cultural heritage • Safe and healthy living conditions	• Indigenous people's rights • Community engagement • Local employment • Secure living
Society	**Consumers**
• Public commitment on sustainable development issues • Contribution to economic development • Prevention and mediation of armed conflict • Corruption • Technological development	• Health and safety • Feedback mechanism • Consumer privacy • Transparency • End-of-life responsibility

Fig. 2 Considered stakeholder groups and subcategories in S-LCA recommended by the UNEP/SETAC (2009) guidelines for S-LCA

three stakeholder groups, namely, worker, customers, and local communities.

The social issues of bio-based product systems are analyzed; for instance by Hasenheit et al. (2016) who summarized possible social indicators to assess a bio-based economy, e.g., the use of agrochemicals, malnutrition, or job quality (see Table 1). The review of Rafiaani et al. (2018) shows common social indicators within the bio-based economy, namely, health and safety, food security, income, employment, land- and worker-related concerns, energy security, profitability, and gender issues. Siebert et al. (2018a, 2018b) define appropriate and relevant indicators for a social assessment of wood-based products within a bioeconomy region in Germany (see Table 1). Another case study of Touceda et al. (2018) assesses the sustainability of a tailored development for housing retrofit. This study does not address a specific wood example. However, they propose wood as a substitute for metallic windows frames. An overview and summary of the social impact topics and possible indicators of these studies is given in Table 1.

The identified social impacts as shown in Table 1 provide an overview of possible impacts of wood-based products and of a bioeconomy and, respectively, bio-based product systems. It has to be noted that each factor is somehow related to other factors, e.g., a change in prices possibly directly or indirectly affects food security in a region (Hasenheit et al. 2016).

3.1.2 Factors influencing methodical choices in S-LCA

The products or sectors assessed within the 50 identified S-LCA case studies range from textiles, sugarcane, car tires

Table 1 Overview of identified social impacts and indicators for assessing bio-based product systems, proposed by Hasenheit et al. (2016) [1], Rafiaani et al. (2018) [2], Siebert et al. (2018a) [3], and Touceda et al. (2018) [4]

Social impact	Possible indicators	
Food security	• Use of agrochemicals, fertilizers [1] • Change in food prices, price volatility [1]	• Malnutrition, risk of hunger [1] • Macronutrient intake/availability [1]
Land access	• Land prices [1] • Access to land (incl. gender equality) [1]	• Land tenure [1] • Property rights (incl. gender equality) [1]
Employment	• Change in employment rate [1] • Job conditions (rate of qualified employees, rate of marginally employed) [1], [3] • Duration of employment (rate of fixed-term employees, rate of employees provided by temporary work agencies) [3] • Full-time equivalent jobs [1]	• Job quality [1] • Need for/lack of highly specialized workforce [1] • Working time (contractual working hours, compensation for overtime) [3] • Work-life-balance (access to flexible working time agreements, rate of part-time employees) [3]
Household income /adequate remuneration	• Income of employees in bioeconomy sector (total) [1] • Payment (payment according to basic wage, average remuneration level) [3]	• Distribution of income [1] • Financial participation (capital participation, profit-sharing and bonuses) [3]
Quality of life	• Change of quality of life [1]	• Equality (of gender, etc.) [1]
Health and safety	• Exposure to agrochemicals [1] • Numbers of multi-resistant organisms [1] • Toxicity of "green" vs. "gray" industrial products [1], [3] • Accidents (occupational (fatal) accidents) [1], [3]	• Occupational diseases per working hour [4] • Sick-leave (number of workdays lost per worker and year, sick-leave days, preventive health measures) [1], [3]
Knowledge capital	• On-the-job training (employees participated in training, support for professional qualification) [3] • Vocational training (rate of vocational trainees, rate of vocational trainees hired) [3]	• Research and development (rate of employees in research and development) [3]
Participation	• Workers participation (works' council, other measures for participation) [3]	
Land- and worker-related concerns	• No possible indicators proposed [2]	
Energy security	• No possible indicators proposed [2]	
Profitability	• No possible indicators proposed [2]	• Investment and return (state) [4] • Avoided costs (state) [4]
Equal opportunities/gender issues	• No possible indicators proposed [2] • Older employees (measures to support older employees) [3] • Minorities (rate of disabled employees, rate of foreign employees) [3]	• Gender equality (rate of female employees in management positions, measures to improve gender equality) [3]
Consumer issues	• Indoor air quality [4] • Adequate indoor temperature [4]	• Fuel poverty gap (inability to afford keeping a home warm at a reasonable price) [4]

to recycling systems or manufacturing companies (Table 3). Out of the 50 S-LCA case studies, seven case studies have been identified, which analyze bio-based product systems (e.g., Pizzirani et al. 2018; Siebert et al. 2018a or Agyekum et al. 2017), and one case study has been identified directly related to the automotive industry (Zimmer et al. 2017) (Table 3). These are the basis to identify possible relevant stakeholder groups, subcategories, and/or indicators.

The importance of a sector-specific and geographical context has already been mentioned in several papers in the past (e.g., Benoît et al. (2010) highlight the need of site-specific data; Dreyer et al. (2010a) conclude that the regional context and the industry itself highly influence the external risk environment). The geographical context might also influence the choice of indicators, e.g., in the USA the risk of child labor is considered to be lower compared with, e.g., India or countries with high poverty rates, whereas for other indicators, the opposite is the case (e.g., the risk of not having collective bargaining rights) (Arvidsson et al. 2015; Benoit-Norris et al. 2012). Because of the importance of the regional context in S-LCA (Dreyer et al. 2010a; Jørgensen 2013), it is reasonable to assume that stakeholder groups, subcategories, and/or indicators are chosen on the basis of the geographical context and country. Therefore, investigated countries in the case studies analyzed are split into developing and developed countries based on the United Nations (2014) (see also in Petti et al. 2018). The countries chosen in S-LCAs of bio-based product systems are highlighted with an asterisk in Table 2. The case study within the automotive industry has been conducted for Germany.

An overview of all considered S-LCAs is provided in Table 3, whereby the case studies are categorized by the topic (product system under study) and split up concerning the geographical context (developing and developed countries) (see Table 2).

Slightly more case studies are found for developing countries (29 vs 32), whereby several case studies are conducted for more than one country, including both developing and developed countries. The chosen product system, company, or sector is very heterogeneous in both groups. All 50 case studies were analyzed concerning the chosen subcategories based on UNEP/SETAC (2009) in relation to the geographical context, each split in developed and developing countries (see Fig. 3).

The results in Fig. 3 show that 57% of the 50 S-LCA case studies investigated subcategories concerning the stakeholder group worker and 25% investigated subcategories within the stakeholder group local community. Subcategories from the other three stakeholder groups (value chain actors, society and consumers) were examined in 18% of the considered studies.

Regarding the assumption that subcategories might be chosen depending on the geographical context or the economic status of countries (developed and developing countries), no big differences could be identified. The stakeholder groups value chain actors, society, local community, and worker are chosen more often when S-LCAs were conducted in developing countries (biggest differences for the stakeholder group worker). Only for the stakeholder group consumer, more S-LCA case studies are conducted in developed countries. As illustrated within Fig. 3 only six subcategories show slightly bigger differences between developing and developed countries, namely, child labor, fair salary, working hours and access to material resources are chosen more often in developing countries and forced labor, health and safety (consumer) and local employment are more often chosen in developed countries. Of the case studies which analyzed bio-based product systems (see Table 3), six refer to developing and four to developed countries. Within all studies, the subcategory "local employment" is chosen, followed by "health and safety" (9 studies) and 'fair salary' (8 studies). Additionally, more than half of the studies include "social benefits/social security," "equal opportunities/discrimination," "working hours," and "child labor" as subcategories.

3.2 Environmental life cycle assessment

E-LCA has developed to a widely acknowledged tool — used across various areas — for assessing the potential environmental impacts of a product or service system (Finnveden et al. 2009; Guinée et al. 2011; Zimek et al. 2019). It has been standardized within ISO14040/14044 (ISO 2006a, b) and defines four phases of an LCA study: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and the interpretation phase. In the LCI phase, the input/output data of the studied

Table 2 Overview of the chosen countries of the selected case studies split in developing and developed countries

Geographical context	Countries within the considered S-LCA case studies
Developed countries	Australia, Austria, Belgium, Canada*, Croatia, Denmark, Germany*, Greece, Hungary, Ireland, Italy, Japan, the Netherlands, New Zealand*, Portugal, Spain, United States*
Developing countries	Algeria, Angola, Argentina*, Bangladesh, Brazil*, China, Democratic Republic of Congo, East Timor, Ecuador, Equatorial Guinea, Ghana*, India, Indonesia*, Iran*, Israel, Jordan, Kuwait, Malaysia*, Mexico, Mongolia, Morocco, Mozambique, Pakistan, Peru, Rwanda, Sierra Leone, South Africa, South Korea, Taiwan, Thailand, Turkey, Zambia

*Countries chosen in S-LCAs of bio-based product systems

Table 3 S-LCA case studies (product, sector, company) categorized by topic and geographical context (developing and developed countries); some studies are in both categories as some case studies relate to more countries

Topic	Developed countries	Developing countries
Agriculture	Chen and Holden 2017 (dairy farm); Franze and Ciroth 2011 (rose bouquets); Martínez-Blanco et al. 2014 (fertilizers); Teah and Onuki 2017 (recycled P fertilizers)	Franze and Ciroth 2011 (rose bouquets); Martínez-Blanco et al. 2014 (fertilizers); Teah and Onuki 2017 (recycled P fertilizers)
Apparel industry	Lenzo et al. 2017 and Zamani et al. 2018 (textiles)	Mair et al. 2018 (clothing supply chain); Zamani et al. 2018 (textiles)
Automotive industry	Zimmer et al. 2017 (automotive industry)	Zimmer et al. 2017 (automotive industry)
Bio-based product systems	do Carmo et al. 2017 (biodiesel); Pizzirani et al. 2018 (radiata pine); Siebert et al. 2018a (wood-based products)	do Carmo et al. 2017 (biodiesel); Agyekum et al. 2017 (bamboo bicycle frames); Ghaderi et al. 2018 (switchgrass-based bioethanol); Manik et al. 2013 (palm oil biodiesel); Souza et al. 2018 (biorefinery scenarios)
Construction (materials), housing	Arcese et al. 2013 (accommodation facilities), Touceda et al. 2018 (housing retrofitting processes)	Dong and Ng 2015 (public housing project); Dong and Ng 2016 (building construction project); Fan et al. 2018 (green residential districts); Hossain et al. 2018 (recycled construction materials); Hosseinijou et al. 2014 (building materials, cement, and steel); Singh and Gupta 2018 (steel)
Energy sector	Corona et al. 2017 (solar power plant); Traverso et al. 2012 (photovoltaic (PV) modules); Tsalis et al. 2017 (energy companies); Kolotzek et al. 2018 (capacitor technologies); Wulf et al. 2017 (rare earth permanent magnet for use in wind turbines)	Tseng et al. 2017 (wind power); Kolotzek et al. 2018 (capacitor technologies); Wulf et al. 2017 (rare earth permanent magnet for use in wind turbines)
Food sector	Neugebauer et al. 2017 (tomatoes); Andrews et al. 2009 (tomatoes); Arcese et al. 2017 (wine); de Luca et al. 2018 (Calabrian olives); Petti et al. 2018a (tomatoes); Sanchez Ramirez et al. 2014 (wine company)	Neugebauer et al. 2017 (tomatoes); Du et al. 2018 (sugarcane); Prasara-A and Gheewala 2018 (sugar)
Waste management	Lehmann et al. 2011 (water resources management and integrated packaging waste)	Lehmann et al. 2011 (water resources management and integrated packaging waste); Aleisa and Al-Jarallah 2018 (waste management system); Aparcana and Salhofer 2013 (recycling systems); Mirdar Harijani et al. 2017 (municipal solid waste); Opher et al. 2018 (urban domestic water reuse alternatives)
others	Reuter 2016 (lithium-ion batteries); Schau et al. 2012 (remanufactured alternators); Dreyer et al. 2010b (manufacturing companies); Hannouf and Assefa 2018 (high-density polyethylene, HDPE); Subramanian et al. 2018 (nano-enabled biocidal paint)	Reuter 2016 (lithium-ion batteries); Schau et al. 2012 (remanufactured alternators); Dreyer et al. 2010a (manufacturing companies); Sanchez Ramirez et al. 2014 (cocoa soap); Wang et al. 2017 (IC packaging)

system is collected and analyzed (ISO 2006a). The LCIA phase includes three mandatory elements: first, the selection of impact categories, category indicators, and characterization models; second, assigning inventory results to impact categories; and third, calculating the category indicator results (ISO 2006b). The calculation of LCIA can be done by using an LCIA method (Table 4), which combines a number of category indicators as well as calculates the results based on specific characterization models (Hauschild et al. 2013) and are partly implemented in LCA software (Rosenbaum et al. 2018). LCIA methods exist for midpoint level (CML 2002, EDIP, TRACI) and endpoint level (EPS, Eco-Indicator 99) as well as methods that try to combine the mid- and endpoint levels (LIME, ReCiPe, IMPACT 2002+) (EC 2010c; Hauschild et al. 2013; Pennington et al. 2004) (Table 4). On midpoint level, a higher number of impact categories are differentiated, and at endpoint level, the impacts are shown as effects on the areas of protection (human health, natural environment, natural resources) (EC 2010c; Pennington et al. 2004; Udo de Haes et al. 1999; Udo de Haes et al. 2002) or aggregated as a single score (e.g., eco-indicator).

3.2.1 Environmental issues of wood in automotive applications

To identify the environmental issues of wood in automotive applications, literatures dealing with bio-based and automotive product systems have been analyzed in regard to relevant environmental issues connected with specific materials as well as in regard to methodical aspects connected with either product system. Starting with LCAs of bio-based product systems, the first tangible LCAs for the forestry and wood products sector in Europe were published in in the 1990s (e.g., Frühwald and Wegener 1993 or Karjalainen and Asikainen 1996). Since then LCA has been frequently applied to assess the impacts of wood

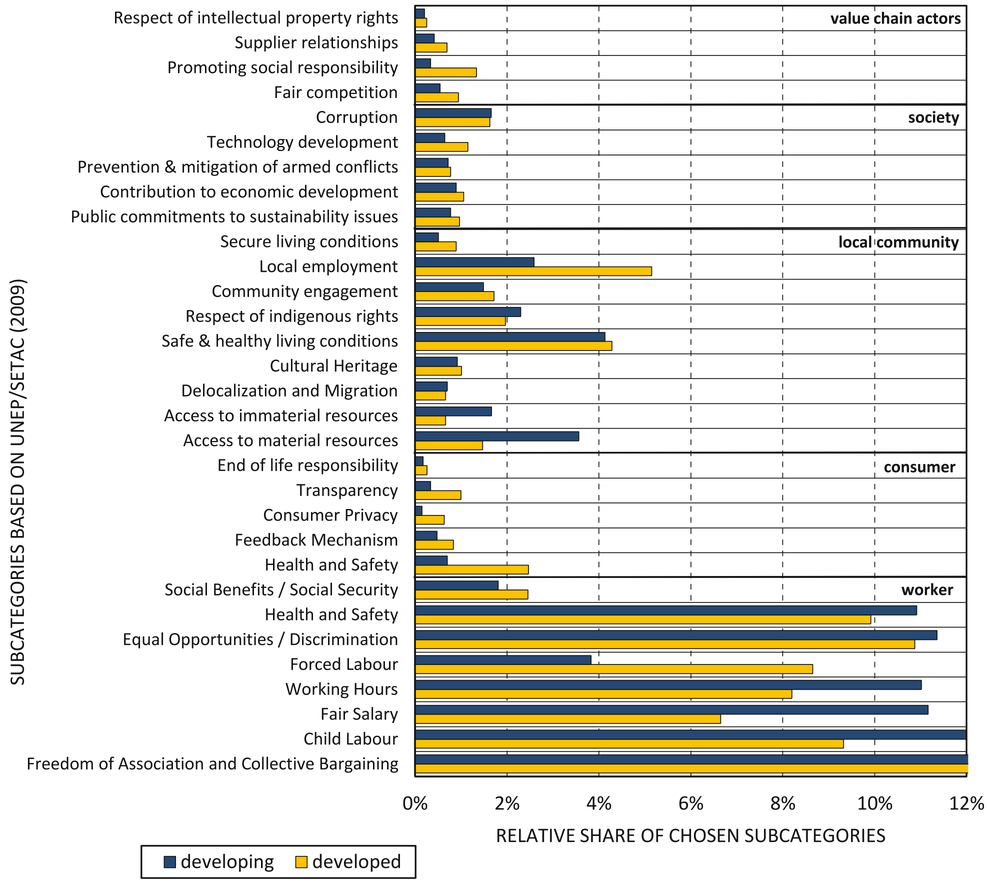


Fig. 3 Chosen subcategories based on UNEP/SETAC (2009) split in developing ($n = 32$) and developed ($n = 29$) countries (relative to total amount of the selected subcategories by the reviewed case studies)

and wood-based products (see, e.g., Petersen and Solberg 2004, González-García et al. 2011b, Hesser et al. 2016 or Lettner et al. 2018). However, as, for example, stated by Klein et al. (2015), there are still no consistent and comprehensive LCA studies of wood-based production systems. Due to the multitude of different methods and approaches (e.g., see Hesser 2015 in terms of carbon accounting or Sutterlüty et al. 2017 in terms of water footprint), it is difficult to make a comparative statement between different studies.

Table 4 Overview of existing LCIA methods including the respective year and geographical origin of each method (Rosenbaum et al. 2018)

LCIA methods	Year	Origin
CML	2001	Netherlands
ReCiPe	2009	Netherlands
Eco-Indicator	1995	Netherlands
IMPACT 2002+	2002	Switzerland
TRACI	2003	USA
EPS	2000	Sweden
EDIP	2003	Denmark
LUCAS	2007	Canada
LIME	2003	Japan
ILCD	2012	EU
EcoScarcity	2006	Switzerland
BEES	1997	USA
IMPACT World+	2016	Canada, USA, Denmark, France, Switzerland
LC-IMPACT	2016	EU

When performing comparative LCAs of bio-based materials in comparison with petrochemical materials, Pawelzik et al. (2013) argue that the treatment of biogenic carbon storage is critical for quantifying the greenhouse gas emissions. However, a current shortcoming frequently discussed in the LCA community is the difficulty to fully capture the dynamic nature of carbon flows (see, e.g., Brandão et al. 2013; Lippke et al. 2011; McKechnie et al. 2011). Also, the question of whether to account for carbon storage or not is subject to ongoing debates (Levasseur et al. 2012; Pawelzik et al. 2013). The questions concerning carbon accounting are closely connected to the questions concerning land use. IPCC (2006) and EC (2010a) have published specific guidelines for calculating the carbon stock for agriculture and forestry land use. Besides following a more simplified approach, the guideline published by EC provides the possibility to calculate changes in total of carbon stocks for different soil types or land cover (Pawelzik et al. 2013).

Klein et al. (2015) reviewed LCAs in the forestry sector and found that all reviewed studies considered the global warming potential as impact category, yet, solely focusing on climate change as impact category may not be sufficient. In general bio-based products and an increased cultivation of biomass are connected to the risk of biodiversity loss (Koh 2007; Koh and Ghazoul 2008; Pawelzik et al. 2013). Assessing the loss of biodiversity as well as water use or soil degradation are often excluded in LCAs due to persisting methodological problems and limited data availability (dos Santos et al. 2014; Pawelzik et al. 2013). In order to overcome this limitation, the impact categories global warming, acidification, eutrophication, and ecotoxicity currently cover the main drivers of biodiversity losses (dos Santos et al. 2014; Pawelzik et al. 2013). With the impact categories fresh water aquatic ecotoxicity and terrestrial ecotoxicity, the issues of water and soil protection can be evaluated (dos Santos et al. 2014). Nevertheless, it is worth to note that methodological differences within each proxy should be considered individually. The cumulative energy demand is often used as a proxy indicator in LCA studies (Huijbregts et al. 2006).

Klein et al. (2015) focused on the methodological aspects of forest production and highlighted the large ranges of results in dependence on methodological choices, such as system boundaries and functional unit. In terms of system boundaries, most of the reviewed studies followed a cradle to gate approach. While the endpoint in the individual studies was very similar, the starting point for the assessment at the forest site varied considerably. Most of the studies actually started at the harvesting thinning/operations and thus excluded other processes such as seedling/seed production or planting (Klein et al. 2015). At the end, most of reviewed studies investigated wood for energy purposes or for pulp wood. Another aspect is the determination of the functional unit. In total Klein et al. (2015) identified 12 different functional units applied in the 24 studies. Furthermore, around 50% of the studies did not mention any characteristics of the wood or the wood-based product.

In E-LCAs focusing on automotive product systems, the potential benefits of lightweighting are often the objective of the studies since weight reduction of vehicles can lead to major environmental benefits (Hottle et al. 2017). Hottle et al. (2017) found in their review on critical factors affecting LCAs that the use phase for vehicles with combustion engines accounts for 84–88% of the life cycle emissions and energy demand, whereas the production just accounts for about 4–7% of the energy consumption. However, the production and processing of materials can have dramatic impacts on the environment like undesirable emissions to air, water, and land or land use pattern and water use (Allwood et al. 2011).

The most commonly used material in the automotive industry is steel (Poulikidou et al. 2015), which makes up about 65–70% of the body mass (Dalmijn and de Jong 2007). Typical lightweight alternatives are high-strength steels, aluminum, magnesium, and glass or carbon fiber composites (Hottle et al. 2017; Mayyas et al. 2012b; Poulikidou et al. 2015; Raugei et al. 2015; Witik et al. 2011). All those materials are non-renewable and will eventually be exhausted up to the point where it will be too expensive to extract them; wherefore, the depletion potential and in some cases the scarcity needs to be assessed (Allwood et al. 2011; Cordella and Hidalgo 2016; Klinglmair et al. 2014).

Depending on the material to be assessed, different environmental issues are of concern, and the results vary considering different impact categories. For example, current used lightweight materials such as composites do indeed reduce weight, but the recycling is difficult, toxic, and energy intensive (Allwood et al. 2011; Diener and Tillman 2016). Consequently, using composites can lead to problems in reaching the ELV targets (European Commission 2000). Besides that, glass fibers need approximately four times more energy in the production compared to kenaf fibers (Mohanty et al. 2001) or jute fibers (Alves et al. 2010). Although natural fiber-reinforced composites may be seen as sustainable in terms of integrating renewable materials, they are not sufficiently eco-friendly because of their petroleum-based matrix (Mohanty et al. 2002).

Hottle et al. (2017) reviewed LCAs of materials for vehicle mass reduction and found that most studies assessed GHG emissions and life cycle energy use. This makes sense since those impacts are the main concern for the aluminum industry (Liu and Müller 2012) as well as for the production of magnesium (Cherubini et al. 2008). Liu and Müller (2012) mention other impact categories which should be assessed when analyzing aluminum: the toxicity of the aluminum production through emissions to air, water, and soil as well as the land use of bauxite mining and red mud generation (Liu and Müller 2012). Aluminum is ranked under the top 10 for its land use change, fresh water ecotoxicity, and final solid waste production in a top twenty priority list for the environmental profiles of materials consumed in the Netherlands (Liu and Müller 2012; van der Voet et al. 2003). van der Voet et al. (2003) published a report named "dematerialization: not just a matter of weight" where a contribution of materials to 13 environmental impact categories consumed in the Netherlands is provided. They screened and summarized for each impact category the top 20 contributions of materials to environmental problems. Their results show that steel and iron contribute to *depletion of abiotic resources*, *land use competition*, as well as *fresh water ecotoxicity* (van der Voet et al. 2003). The materials such as high-alloyed steel, aluminum, and plastics contribute at least to ten out of 13 impact categories (Table 5).

3.2.2 Factors influencing methodical choices in E-LCA

In total 33 E-LCA case studies of wood-based products and 32 E-LCA case studies of automotive components were identified. An overview of the identified E-LCA case studies is provided in Table 6, where the 65 case studies are categorized according to the focus of the study (E-LCA of wood or automotive

Table 5 Environmental problems of selected materials (van der Voet et al. 2003)

	Steel and iron	Steel-high alloyed	Aluminum	Plastics
Depletion of abiotic resources	x	x	x	x
Land use competition	x	x	x	x
Climate change			x	x
Stratospheric ozone depletion			x	x
Human toxicity		x	x	x
Fresh water ecotoxicity	x	x	x	x
Marine ecotoxicity		x	x	x
Terrestrial ecotoxicity		x	x	x
Photochemical oxidant formation		x	x	x
Acidification		x	x	x
Eutrophication				
Radiation		x	x	x
Final solid waste		x	x	

components) and the objective of the reviewed studies. The objectives of E-LCA literature were grouped into six categories: method development, impacts of lightweighting, material substitution, re-/eco-design, material development, and life cycle inventory. A description of each category is provided in Table 7.

Besides studying the E-LCA literature for the objective, it was further analyzed for the chosen impact categories (Table 8) and LCIA methods (Table 4). For further analysis, the LCIA methods rarely used in the studies (EPS, EDIP, ILCD, BEES) as well as the characterization model USEtox are grouped into "Others." Another possibility to do the LCIA is by calculating the cumulative energy demand (CED) (Huijbregts et al. 2006; Huijbregts et al. 2010). Several studies calculated the global warming potential (GWP) by referring to the latest IPCC characterization factors (IPCC 2013) which is also included in several LCIA methods like in CML. Some studies did not mention a particular LCIA approach but performed own calculation with, e.g., energy-related indicators — those studies were categorized into the LCIA group own calculations.

A common practice is to explain the choice of certain impact categories and indicators by referring to previous studies with a similar research focus, which is also suggested by Höglmeier et al. (2016). However, the use of categories that have been selected in comparable studies does not mean that all relevant aspects are automatically taken into account. Therefore, the literature sample was screened to identify the impact categories chosen to assess wood as well as automotive product systems. In total over 50 differently named impact categories were identified in the E-LCA sample. An overview of all identified impact categories is provided in the appendix. In order to identify potential tendencies between impact category choice and, e.g., the analyzed material as well as to reduce the complexity of the identified impact categories, those over 50 identified impact categories were grouped into 14 impact category groups (Table 8) according to the overview provided by Rosenbaum (2018). The grouping was done (a) on the basis of the unit used to express an impact category, (b) based on the theme addressed, e.g., the CA group contains carcinogenic and non-carcinogenic impact categories (c) if similar environmental issues were addressed as in the groups BD and RRU, and (d) when the impact category was used just once or twice they were included into a group *others*. A more detailed overview of the grouping including the units and their respective LCIA methods is provided in the appendix.

The results of the content analysis show that more than half of the studies used software support to perform the E-LCA. Most of them used SimaPro followed by GaBi, Umberto, OpenLCA, or ATHENA. Using software support can influence the choice of an LCIA method since those software solutions have various LCIA methods implemented (Rosenbaum et al. 2018; SimaPro 2019). Incidentally, 78% of the studies which performed own calculation had no LCA software support. The availability of the characterization sheet of an LCIA method could be another argument for choosing one LCIA method over the other. The results of the present study show that 56% of the studies where TRACI was chosen for LCIA used no software support. The environmental impact assessment tool TRACI includes characterization factors for the LCIA and is available for free at the EPA homepage (EPA 2016). The same is possible with CML-IA, where the characterization factors can be downloaded at the homepage of Leiden University.[2]

[2] https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

Table 7 E-LCA literature sample ($n = 65$) categorized by focus and aim of the study

Aim	Focus	Author(s) (year of publication)
Method development	Wood	Höglmeier et al. (2014)
	Automotive	Poulikidou et al. (2015), Mayyas et al. (2012b), Ribeiro et al. (2007), Geyer (2008), Fitch and Cooper (2003)
Impacts of lightweighting	Automotive	Das (2000), Das (2014), Duflou et al. (2009), van Acker et al. (2009), Kim et al. (2010), Geyer (2008), Raugei et al. (2015), Ding et al. (2016), Delogu et al. (2017), Koffler (2014)
Material substitution	Wood	Petersen and Solberg (2004)
	Automotive	Akhshik et al. (2017), Alves et al. (2010), dos Santos et al. (2014b), Das (2011), Dubreuil et al. (2012), Hardwick and Outteridge (2016), Puri et al. (2009), Sun et al. (2017), Song et al. (2009), Tharumarajah and Koltun (2007), Witik et al. (2011), Wötzel et al. (1999), Zah et al. (2007)
Re-design/ Eco-design	Wood	Bolin and Smith (2011a, 2011b, 2011c), Cobut et al. (2015), dos Santos et al. (2014), Frenette et al. (2010), González-García et al. (2011a), González-García et al. (2011b), González-García et al. (2012), Hesser et al. (2016), Lee and Xu (2004), Lu and El Hanandeh (2016), Noda et al. (2016), Petersen and Solberg (2002)
	Automotive	Boland et al. (2016), Ermolaeva et al. (2004), Ribeiro et al. (2007)
Material development	Wood	Hesser (2015), La Rosa et al. (2014), Mahalle et al. (2014), Sommerhuber et al. (2017), Xu et al. (2008)
	Automotive	Luz et al. (2010)
Life cycle inventory	Wood	Cambria and Pierangeli (2012), García-Durañona et al. (2016), Gasol et al. (2008), González-García et al. (2009), Hu et al. (2018), Laurent et al. (2013), Nakano et al. (2018), Park et al. (2018), Petersen and Solberg (2004), Phungrassami and Usubharatana (2015), Rivela et al. (2007; 2006), Wenker et al. (2016)
	Automotive	Hakamada et al. (2007)

Studies mentioned more than once means that multiple objectives were formulated

Other influencing factors for the choice of an LCIA approach might be the availability and up-to-dateness of a method as well as the geographical scope of the study. In the reviewed E-LCA literature CML was used only after the year 2006, ReCiPe after 2013, TRACI and IMPACT2002+ only after 2009, and Ecoindicator95/99 only before 2010. Looking at the year when a certain LCIA method was first introduced (Table 4) plus a few years until a study first uses a new method, the results are not surprising. The geographical focus of a study can also influence the choice of an LCIA method, e.g., all studies which defined the geographical scope to be North America used TRACI as LCIA method.

From the 65 studies, 95% considered climate change (CC) impact categories. Over 60% assessed acidification and eutrophication whereas ozone depletion, abiotic resource use, respiratory effects, or impacts measured by energy demand have been analyzed by over 50%. Just little difference could be found between impact category choice and focus of the study, but, e.g., bio-based materials were more often analyzed with impact categories like acidification, abiotic resource use, eutrophication, or ecotoxicity (Fig. 5). The latter can at least be partly

Table 6 Objectives of the reviewed E-LCA studies

Aim	Description
Method development	The study focused on (further) developing a method, framework, or model for sustainable material selection, assessing lightweight strategies, for life cycle engineering or for assessing cascading systems
Impacts of lightweighting	Several studies analyzed the potential benefits of a weight reduction by calculating the emission saving potentials of using lighter materials for the vehicle
Material substitution	The focus was on assessing the environmental impacts of constructing a component or product with a different material. The focus of the study was on the material of a certain component
Re-design / Eco-design	The studies focused on environmental conscious product development and therefore on assessing the environmental impacts of redesigned or eco-designed components or products and often involved more components and materials
Material development	The studies assessed the environmental impacts of newly developed materials and compared them with conventional materials
Life cycle inventory	The objective of the study was on producing generic LCI data for a region, life cycle stage, material, product, or certain practices as well as in some cases to identify hotspots in the product system

Table 8 Overview of the identified impact categories in the reviewed literature grouped into 14 category groups for further analysis. A more detailed overview is available in the appendix

Acronym	Category	Impact categories
AC	Acidification	Terrestrial or aquatic acidification
ARU	Abiotic resource use	Abiotic depletion potential, fossil fuel depletion, mineral extraction
BD	Biodiversity and land use	Land occupation, biodiversity, biotic production potential
CA	Carcinogenic effects	Carcinogenics and non-carcinogenics
CC	Climate change	Global warming potential, GHG emissions
ED	Energy demand	Cumulative energy demand, cumulative non-renewable energy use
ET	Eutrophication	Marine or terrestrial eutrophication
Etox	Ecotoxicity	Aquatic ecotoxicity, terrestrial ecotoxicity
HT	Human toxicity	Human toxicity potential
IR	Ionizing radiation	Ionizing radiation
OD	Ozone depletion	Ozone layer depletion
Others	-	Solid waste, heavy metals, pesticides
RE	Respiratory effects	Respiratory effects organics and inorganics, smog potential, photo-oxidants creation potential
RRU	Renewable resource and water use	Consumption of renewable resources, water intake, water depletion

explained by the fact that E-LCAs of wood products chose more often CML as an LCIA method which already includes several different impact categories (Fig. 4).

Numerous different materials were analyzed in the E-LCA literature. In order to analyze relations between a material and the LCIA method or impact category for bio-based materials in the automotive industry, the materials were categorized into eight material groups (*glass or carbon fiber composites* (G/CFRC); *steel* (including boron, stainless, or high strength steel); *aluminum*, *wood and engineered wood products* (e.g., wood, glulam, MDF, OSB, or particleboards); *plastics* (e.g., polypropylene); *natural fiber reinforced composites* (NFRC, e.g., with kenaf, jute or wood); *magnesium*; and *other materials* (e.g., mineral reinforced composites or concrete)). The latter two were not considered for further analysis.

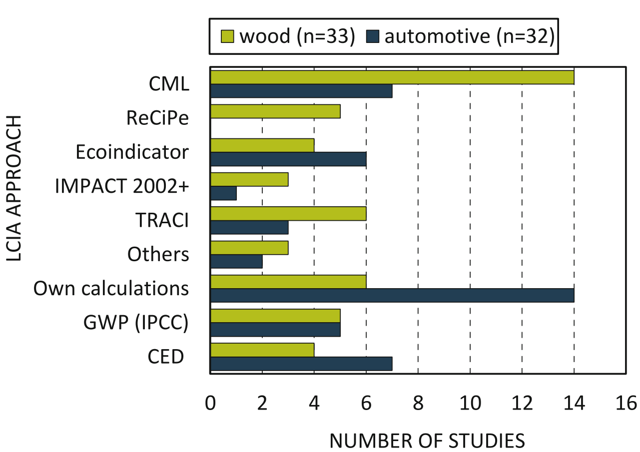


Fig. 4 LCIA approaches chosen by the reviewed E-LCA studies either focusing on wood or on automotive (absolute numbers). Some case studies chose more than one LCIA approach

The impact category choice per material analyzed is illustrated in Fig. 5. Figure 6 illustrates the LCIA method chosen for assessing different materials. When just comparing the choice of impact categories between two materials, especially when comparing bio-based (natural fiber reinforced composites and engineered wood products) versus steel, aluminum, and composites, the results show that the latter materials were more often analyzed with energy-related impact categories. The studies analyzing bio-based materials more often chose various impact categories. However, this can also be explained by the fact that studies focusing on wood more often used CML for LCIA (see Fig. 4) which already includes different impact categories, whereof automotive studies more often did the LCIA with own calculations. Most studies, which did not mention any LCIA approach, performed their own calculations or added impact categories not covered in their chosen LCIA method (mostly climate change and/or energy demand impacts). The materials assessed in the "own calculation" studies are steel (48%) and aluminum (58%) (Fig. 6).

Analyzing the LCIA approach chosen per objective of a study, the results show that studies focusing on *material development* and *life cycle inventory* more often chose CML, whereas studies focusing on *impacts of lightweighting* and *method development* more often performed own calculations. The latter might be explained by the fact that automotive studies mostly aimed at

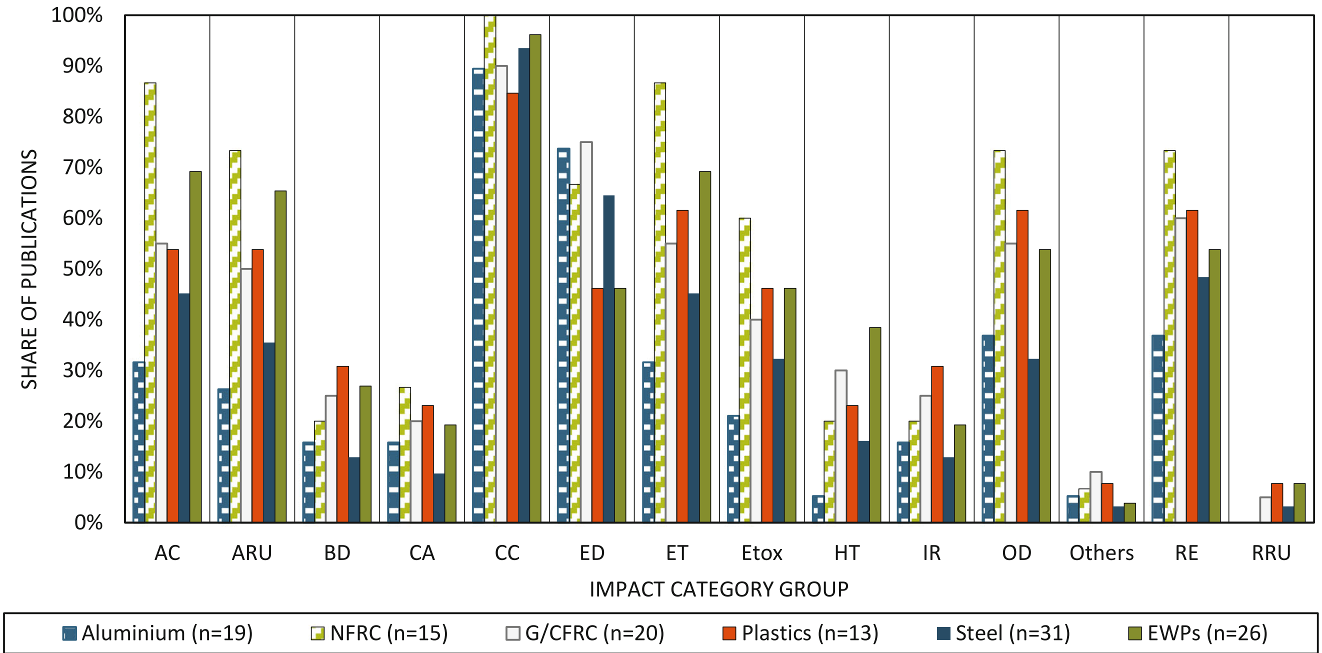
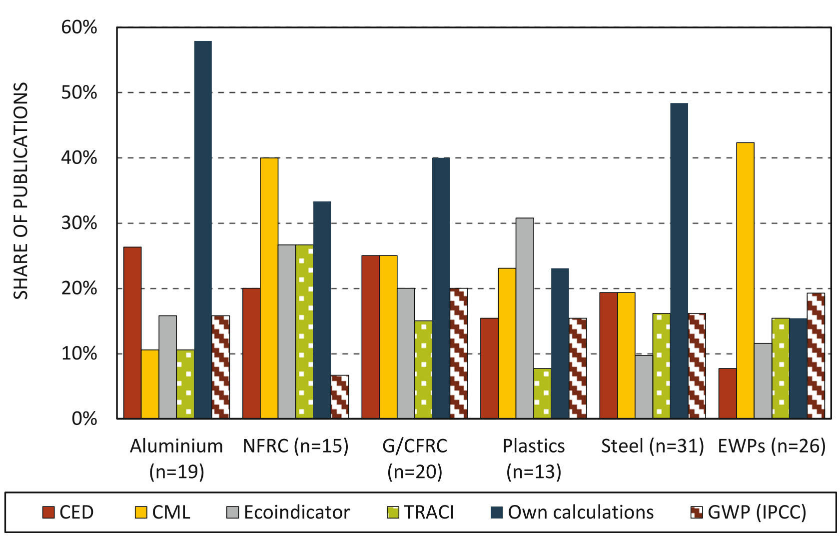


Fig. 5 Impact categories chosen for assessing different materials relative to the total number of studies that examined this material (NFRC - natural fiber-reinforced composites; G/CFRC - glass or carbon fiber-reinforced composites; EWPs - engineered wood products). The description of impact category groups including their abbreviations is provided in Table 8

assessing material substitution effects, identifying potential benefits of lightweighting, or developing a method for sustainable material selection (Fig. 7). On the contrary, E-LCAs of wood products focused more often on *life cycle inventories*, *material development*, or *re-/eco-design*. The results of Fig. 7 are in line with the results presented in Fig. 4: here E-LCAs of wood products more often chose CML whereas automotive E-LCAs more often performed own calculations. All of the automotive studies analyzed the whole life cycle of the product under study. On the contrary, only 45% of the wood E-LCAs considered the whole life cycle in their analysis whereof the other 55% consider just parts of the life cycle, mostly from cradle to grave of which 70% aimed at analyzing the life cycle inventory of several processes.

Fig. 6 LCIA methods chosen for assessing different materials relative to the total number of studies that examined this material (NFRC - natural fiber-reinforced composites; G/CFRC - glass or carbon fiber-reinforced composites; EWPs - engineered wood products)



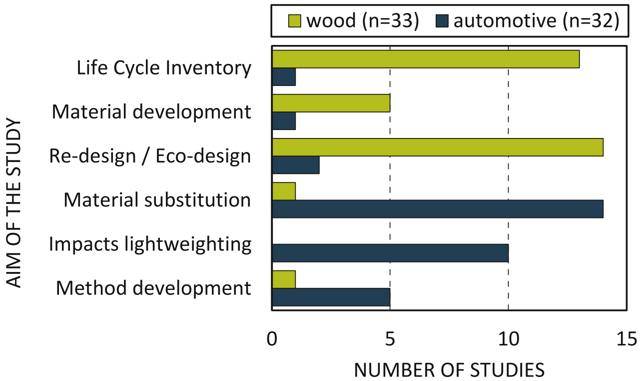


Fig. 7 Aim of the reviewed E-LCA studies either focusing on wood or automotive (absolute numbers)

4 Discussion and conclusion

The aim of the conducted literature review was to identify the relevant social topics and environmental issues when assessing wood in automotive applications as well as to shed light on the factors influencing the choice of the respective methods, impact categories, and indicators. The first step was to gain knowledge about (RQ1) which environmental and social impact categories or subcategories are considered in the literature and secondly to systematically analyze the factors shaping the choice of methods, impact categories, and indicators in environmental and social LCA (RQ2).

4.1 Relevant social and environmental issues

In order to identify relevant social and environmental issues, literature dealing with these topics was reviewed. The results of this review show that most of the S-LCA case studies performed so far, referred to the subcategories proposed by the UNEP/SETAC (2009) guidelines. Additional relevant social topics for bio-based product systems could be identified (see Table 1), such as food security or land- and worker-related concerns. Although the identified social impacts listed in Table 1 can be a good starting point to decide for impact categories and indicators for bio-based product systems, it might not be complete yet. S-LCAs specific for bio-based product systems are still very limited in order to analyze and compare the different methodologies and indicators chosen in the case studies. Furthermore, there is a risk that potentially relevant indicators will be neglected, if only the indicators of the UNEP/SETAC (2009) guideline are taken into account. Nevertheless, the literature suggests that the geographical and sectorial context determine methodical choices in the case of S-LCA (see in Benoît et al. 2010; Dreyer et al. 2010a; Garrido et al. 2018; Hunkeler 2006; Sanchez Ramirez et al. 2014; Siebert et al. 2018a; Siebert et al. 2018b).

Regarding E-LCA the literature suggests that the objective and material type determine calculation approaches and impact category choices (EC 2010c; ISO 2006a; Rosenbaum et al. 2018); for instance, GWP is described as a major concern in the automotive industry as well as in the production of certain materials like aluminum or magnesium (Cherubini et al. 2008; Hottle et al. 2017; Liu and Müller 2012). However, some authors recommend to consider additional impact categories, e.g., biodiversity for bio-based systems, where the main drivers of biodiversity loss can be covered with the impact categories global warming potential, acidification, eutrophication, and ecotoxicity (dos Santos et al. 2014; Klein et al. 2015; Pawelzik et al. 2013); the depletion potential or scarcity indicators for non-renewable materials (Allwood et al. 2011; Cordella and Hidalgo 2016; Klinglmair et al. 2014); or ecotoxicity for steel and toxicity in the case of aluminum (see Table 5) (Liu and Müller 2012; van der Voet et al. 2003).

4.2 Factors influencing methodical choices

To gain insights on the factors that shape the choice of methods and indicators in environmental and social LCA, a content analysis approach of three literature samples (all published S-LCA case studies; E-LCA case studies focusing on wood products or on components in automotive applications) was performed. The sample was analyzed covering the following criteria: considered stakeholder groups and chosen subcategories (S-LCA), sector or product system (S-LCA), year of publication and geographical scope (S-LCA and E-LCA), chosen LCIA method(s) and impact categories, objective(s) of the studies, analyzed materials and used software support (E-LCA).

In S-LCAs the identification of relevant countries and sectors as well as the targeted stakeholder groups is central in order to identify relevant social aspects (subcategories, indicators) (Dreyer et al. 2010a; Jørgensen 2013; UNEP/SETAC 2009). The results of the present study show that the stakeholder groups value chain actors, society, local community, and worker who were chosen slightly more often when S-LCAs were conducted focusing on developing countries. Hereby, the biggest differences can be observed for the stakeholder group worker (see Fig. 3). Only the stakeholder group consumer has been chosen more often for developed countries. In globalized value chains, the steps in the production phase, such as resource extraction, are often located in developing countries; hence, the focus on the stakeholder group workers can be explained. Following, the consumers as stakeholder groups affected during the use-phase are considered in studies conducted in developed countries. This is also reflected in the choice of indicators. The indicators child labor, fair salary, working hours, and access to material resources have been slightly more often chosen in developing countries, and two indicators have been slightly more often chosen in developed countries (forced labor and local employment). For example, in the case of child labor, studies showed that poverty drives this social issue in developing countries because the income of child labor is highly needed (Arvidsson et al. 2015). Following it can be assumed that the socio-political context is reflected in the selection of indicators. However, within the 50 case studies under investigation, the results showed not as many differences as might be expected. It has to be noted that this study included only a small sample, yet it included all available case studies at the date of analysis. No clear connection between the geographical area and the choice of subcategories/indicators could be found within the present study. Petti et al. (2018) did a review on S-LCA and came to a similar conclusion that the geographical area has just a minor influence on the choice of social indicators. They also found that over 40% of the S-LCAs conducted have been performed in European countries where the highest concentration of researchers can be observed (Mattioda et al. 2015; Petti et al. 2018). A general problem in S-LCAs focusing on developing countries might be data availability (Petti et al. 2018). The difficulty in finding data (e.g., socially sensitive ones) could be one reason why fewer studies than expected were conducted in developing countries (Petti et al. 2018). Especially in developing countries, it could be important to implement S-LCAs in order to identify the hotspots to improve the social conditions on site (Petti et al. 2018).

The environmental issues related to the production of materials are diverse, yet most studies focus on assessing the impacts on climate change (95%). Similar results are shown by Hottle et al. (2017) in context of automotive LCAs, which is probably connected to the emission performance standards of the European Commission (2014). The results of the present study show that climate change is also the most chosen indicator in LCAs of wood-based products and Klein et al. (2015) found the same result on LCAs of forest productions. In the analyzed case studies, over 60% assessed acidification and eutrophication, whereas ozone depletion, abiotic resource use, respiratory effects, or impacts measured by energy demand have been analyzed by over 50%. Over 30% of the analyzed case studies focused just on one or two indicators, which is relatively modest considering the environmental issues connected with materials. However, just because a category is chosen by a lot of different studies, it does not imply that this is an environmental issue to be included as recommended by EC (2010b) and ISO (2006a). One way to identify relevant impact categories for a specific product system is to screen results of different impact categories after an LCA study has been performed. Using software support facilitates this since various LCIA approaches covering various impact categories are partly already implemented in LCA software (Rosenbaum et al. 2018; SimaPro 2019). This means the environmental issues connected with a system can at least be identified after the LCA has been performed by analyzing the results of the LCA. If no software support is available, the identification of the relevant environmental issues is more complex and time-consuming than with software support. For that the characterization tables of CML or TRACI can be used, although here data must be available and in the case of ex-ante assessment data availability is an issue. If no resources for software support or generic databases such as Ecoinvent are available, researchers and practitioners have to rely on preliminary studies with a similar research focus. In that way, insights into the relevant environmental issues for specific product systems are gathered, which might help in the selection of impact categories. Another possibility on how to deal with the issue of no software support or no generic database available is to use CED as a proxy for the environmental burden of impacts, as recommended by Huijbregts et al. (2006). However, CED looks only into the primary energy demand, and other environmental impacts are not covered.

In the present study it could be shown that the identification of relevant environmental issues of wood in automotive applications is difficult, also when referring to previous studies with similar research focus. In the studies analyzed, the choice for a certain impact category or LCIA approach was often not argued or was influenced by more than just the environmental issues connected with the system under study. In the conducted literature review influencing factors such as the objective of the study, the up-to-dateness of the LCIA approach, the geographical scope of the study, the materials analyzed, and the software support have been identified by reviewing and analyzing relevant literature. The two investigated samples on E-LCA of wood products and of automotive components had quite different objectives (Fig. 7), which might be one explanation for the different choice of LCIA approaches (Fig. 4). Other influencing factors for methodical choices might be data availability or the usage of software support. The former was rarely mentioned within the studies analyzed. The latter is not always available, e.g., due to limited budgets or tradition (e.g., Excel as the usual tool). The results show that 40% did not mention any software support, of which the majority (80%) did not mention the LCIA approach or calculated the LCIA on their own. However, analyzing the potential environmental impact with a whole set of impact categories is easier when using software support. Other influencing factors might be the up-to-dateness of the LCIA approach or the geographical scope of the study. In case of the geographical scope of the study, it could be shown that it can influence the choice for an LCIA approach, e.g., all studies which defined the geographical scope to be North America used TRACI as LCIA method. Regarding the influence of the material analyzed on the choice of impact category, it was found that studies which analyzed product systems involving wood products or natural fiber composites more often chose impact categories such as acidification, eutrophication, abiotic resource use, or ozone depletion (see Fig. 5). However, this might be connected to the fact that LCAs of wood products more often performed the LCIA with CML (Fig. 4) and therefore with various impact categories.

4.3 Limitations and outlook

The aim of this study was to shed some light on the choice of impact categories and LCIA approach for E-LCA and subcategories and indicators for S-LCA when assessing the environmental and social performance of wood-based components in automotive applications. The applied methods, literature review, and content analysis are subject to some typical limitations, i.e., selection of literature and criteria for coding might be biased by the researcher conducting the study, the aspects discussed depend on other authors work in this field, setting the boundaries according to the research question for the literature search as well as discriminating between relevant and irrelevant literature (e.g., Engert et al. 2016).

Some relevant environmental and social impact categories as well as influencing factors in methodical choices could be identified from existing literature. However, a clear picture on these issues could not be drawn, e.g., concrete recommendations on material-related environmental issues or geographical-related social topics could not be found when reviewing the literature focusing on automotive or wood-based product systems. Expanding the literature sample to include LCAs of other product systems most likely enables to generate additional knowledge on relevant social and environmental issues for specific product systems.

Identifying the relevant impact categories before conducting a study is a general problem (not just for assessing wood in vehicles), and the literature review carried out shows that this problem can be confirmed for the specific case of wood in automotive applications. The results of the present study are based on a small sample, namely, E-LCAs of wood-based or automotive product systems and S-LCA case studies. Further research might analyze if LCAs of other product systems face similar challenges in identifying the relevant environmental and social issues as well as in selecting the appropriate impact categories and assessment methods for the system under study.

Further knowledge on methodical choices might be gained by social science research on, e.g., the motivation of researchers to choose a certain LCIA approach or impact category in E-LCA or subcategory and indicator in S-LCA. This may provide an understanding of what information and guidance researchers and practitioners may consider regarding methodological decisions for specific product systems. A starting point for providing guidance on the identification of environmental and social issues for specific product systems could be based on environmental issues connected with materials or geographical-related social topics. Furthermore, there is currently neither a full E-LCA nor an S-LCA case study of wood-based products for automotive applications available. Such a study would be needed to address the differences in assessing bio-based and non-bio-based products and in particular the extent to which those products are comparable in terms of the different environmental issues that should be considered for each system.

Appendix

Table 9 Categorization of identified impact categories based on Rosenbaum (2018), Jolliet et al. (2003) and Lippiat (2007)

<table>
<tr><th>Acronym</th><th>Category</th><th>Impact category</th><th>Unit</th><th>LCIA method</th></tr>
<tr><td>CC</td><td>Climate change</td><td>global warming potential</td><td>kg CO2 eq</td><td>IMPACT2002+ | EI99 | TRACI | CML | EDIP | ReCiPe | ILCD | IMPACTworld+ | BEES</td></tr>
<tr><td></td><td></td><td>greenhouse effect</td><td>GWP kg</td><td>EI95</td></tr>
<tr><td>ED</td><td>Energy demand</td><td>cumulative energy demand</td><td>MJ</td><td>CED | ILCD</td></tr>
<tr><td></td><td></td><td>primary energy consumption</td><td>MJ</td><td>TRACI</td></tr>
<tr><td></td><td></td><td>Cumulative non-renewable energy use</td><td>MJ</td><td></td></tr>
<tr><td></td><td></td><td>non-renewable energy</td><td>MJ primary</td><td>IMPACT2002+ | EI99</td></tr>
<tr><td>ARU</td><td>Abiotic resource use</td><td>abiotic depletion fossil and non-fossil resources</td><td>MMBTU</td><td></td></tr>
<tr><td></td><td></td><td>abiotic depletion potential (non-renewable resources)</td><td>ADP | person reserve | marginal increase of extraction costs | kg Sb-eq.</td><td>CML-IA | EDIP | ReCiPe | ILCD</td></tr>
<tr><td></td><td></td><td>resource intensity</td><td>kg</td><td>ILCD</td></tr>
<tr><td></td><td></td><td>fossil fuels depletion / fossil use</td><td>MJ deprived</td><td>EI99 | TRACI | IMPACTworld+ | BEES 2.0</td></tr>
<tr><td></td><td></td><td>Mineral, Metal extraction / depletion</td><td>MJ surplus | kg eq. Of iron in ore</td><td>IMPACT2002+ | EI99 | IMPACTworld+ |ReCiPe</td></tr>
<tr><td>RRU</td><td>Renewable resource and water use</td><td>water intake</td><td>liters</td><td>BEES 2.0</td></tr>
<tr><td></td><td></td><td>water deprivation</td><td>m3 world eq.</td><td>ILCD | IMPACTworld+</td></tr>
<tr><td></td><td></td><td>consumptive water use</td><td></td><td>EI99</td></tr>
<tr><td></td><td></td><td>water depletion</td><td></td><td>EI99 | ReCiPe</td></tr>
<tr><td></td><td></td><td>wood consumption</td><td>t softwood standing trees</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td>EDIP</td></tr>
</table>

Table 9 (continued)

Acronym	Category	Impact category	Unit	LCIA method
		consumption of renewable resources		
AC	Acidification	winter smog		EI95
		acidification	H+ eq.	EI99 | BEES 2.0
		terrestrial acidification	kg SO2 eq | H+ eq. | BS [m2*y] | mol H eq.	IMPACT2002+ | CML-IA | TRACI | EDIP | ReCiPe | ILCD | IMPACTworld+
		aquatic acidification	kg SO2 eq	IMPACT2002+ | IMPACTworld+
OD	Ozone depletion	ozone layer depletion	kg CFC-11 eq	IMPACT2002+ | EI99 | TRACI | CML | EDIP | ReCiPe | ILCD | IMPACTworld+ | BEES
ET	Eutrophication	marine eutrophication	kg N | vkgN N-lim	ReCiPe | ILCD | IMPACTworld
		eutrophication	N eq	EI99 |BEES 2.0
		terrestrial eutrophication	PO^{3-}_4 eq | m2 | mol N eq.	CML-IA | IMPACT2002+ | EDIP | ILCD
		freshwater eutrophication	PO^{3-}_4 eq. | kg PO4 P-lim | NO3eq. | kg N | kg P	IMPACT2002+ | CML-IA | TRACI | EDIP | ReCiPe | ILCD | IMPACTworld+
Etox	Ecotoxicity	ecotoxicity	CTUe | 2,4-D eq	EI99 | BEES
		aquatic ecotoxicity	kg TEG water	IMPACT2002+
		freshwater aquatic ecotoxicity	kg 1,4-Dbeq| 2,4-Deq. | m3 | PAF | CTU	CML | TRACI | EDIP | ReCiPe | ILCD | IMPACTworld+
		marine aquatic ecotoxicity	kg 1,4-Dbeq	CML | ReCiPe
		terrestrial ecotoxicity	kg 1,4-Dbeq | kg TEG soil | m3	CML | IMPACT2002+ | EDIP | ReCiPe
		marine sediment	kg 1,4-Dbeq	CML
		freshwater sediment	kg 1,4-Dbeq	CML
		water pollution	kg	
RE	Respiratory effects	respiratory effects organics	kg C2H4 eq | nmVOCeq | person*ppm*h	IMPACT2002+ | EI99 | EDIP | ReCiPe | IMPACTworld+
		respiratory effects inorganics	PM2.5 eq | PM10 eq.	TRACI | IMPACT2002+ | EI99 | ILCD | IMPACTworld+
		particulate matter formation	PM10eq.	ReCiPe
		photo-oxidants creation potential	C2H4 eq. | ethylene eq.	CML | IMPACT 2002+
		summer smog	POCP kg	EI95
		nitrogen oxides	Nox eq.	TRACI
		smog potential	O3 eq. | NOx eq	TRACI | BEES
IR	Ionizing radiation	ionizing radiation	Bq C-14 eq | DALY | man. Sv/kBq	IMPACT2002+ | EI99 | CML | ReCiPe | IMPACTworld+
HT	Human toxicity	human health	C7H8 eq	BEES 2.0
		criteria air pollutants	microDALYs	BEES 2.0
		human toxicity potential	kg 1,4-DCBeq | 2,4Deq | chloroethylene eq. | m3 | cases | CTU	IMPACT2002+ | TRACI | CML | EDIP | ReCiPe | ILCD | IMPACTworld+
CA	Carcinogenic effects	carcinogenics	kg benzene | PAH eq. | kg C2H3Cl eq	TRACI | EI99 | EI95 | IMPACT2002+
		noncarcinogenics	kg toluene | kg C2H3Cl eq	TRACI | IMPACT2002+
BD	Biodiversity and land use	land use		EI99
		land occupation	m2org.arable | m2 occupation or transformation	IMPACT2002+ | ReCiPe
		habitat alteration	T&E count	BEES 2.0
		biodiversity	ha eq.	IMPACTworld+
		erosion resistance potential	kg/m^2 | ton/ha/y	ILCD | IMPACTworld+
		mechanical filtration potential	m^3/m^2 | cm/d	ILCD | IMPACTworld+
		groundwater replenishment	m^3/m^2	ILCD
		biotic production potential	kg/m^2 | tC/ha/y	ILCD | IMPACTworld+
			mm/y	IMPACTworld+

Table 9 (continued)

Acronym	Category	Impact category	Unit	LCIA method
		freshwater recharge potential		
		chemical filtration potential	cmol/kg soil	IMPACTworld+
-	Others	solid waste	kg | volume to landfill	BEES
		heavy metals	Pb eq.	EI95
		environmental load Unit	ELU	EPS
		pesticides	active ingr.	EI95

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