sustainable chemistry

MDPI

Communication

Bio-Based Chemicals from Dedicated or Waste Biomasses: Life Cycle Assessment for Evaluating the Impacts on Land

Daniele Cespi [1,2]

[1] Department of Industrial Chemistry "Toso Montanari", University of Bologna, Viale del Risorgimento 4, 40136 Bologna, Italy; daniele.cespi2@unibo.it

[2] Center for Chemical Catalysis—C3, Alma Mater Studiorum Università di Bologna, Viale del Risorgimento 4, 40136 Bologna, Italy

Abstract: Green chemistry and engineering encourage the usage of renewable sources, in replacement fossil fuels. The sector of bio-based products is one of the most predominant examples of such replacements in different fields. However, the impact of biomasses usage is far from being negligible or net zero. A life cycle perspective is required in order to assess all the different environmental impacts related to biomass exploitation and usage, in particular when dedicated sources are used. This study points out the importance of including the results of a Life Cycle Assessment (LCA) early in the design of new bio-based products, to identify the stage of the value chain with the greatest hotspots and set proper eco-design strategies. At the same time, the use of the LCA results may support purchasing activities through comparing products with different burdens. In this manuscript, a focus on land compartment is carried out, given its relevance to the cultivation phase. Five analysis methods are selected for further description. Three are classified as multi-impact approach methodologies (ReCiPe 2016, IMPACT World + and EF 3.0) since they are able to translate mass and energy balances into several impact categories at the same time, not only those on land comparts which are also included. In addition, the LANCA® model and the True pricing method for agri-food products are discussed, underlining the importance of their usage when a detailed review of the impact on soil is necessary (e.g., during an environmental impact assessment). They are compared in this paper, underlining the main differences and potential fields of application.

Keywords: life cycle assessment; bio-based products; impacts on land; LCA; multi-impact approaches; ReCiPe 2016; IMPACT World +; EF 3.0; the LANCA® model; the True pricing method for agri-food products

check for updates

Citation: Cespi, D. Bio-Based Chemicals from Dedicated or Waste Biomasses: Life Cycle Assessment for Evaluating the Impacts on Land. *Sustain. Chem.* **2023**, *4*, 184–196. https://doi.org/10.3390/suschem4020014

Academic Editors: Bommanna G. Loganathan and Florent Allais

Received: 24 February 2023
Revised: 20 April 2023
Accepted: 21 April 2023
Published: 26 April 2023

1. Introduction

Chemistry represents one of the main pillars of our era. According to the green chemistry discipline [1], the journey toward a benign-by -design society [2] goes through the adoption of 12 fundamental principles. Those, together with the principles of green engineering [3], represent key concepts that should be adopted at an early design stage of each innovation (e.g., catalyst, monomer, intermediate/final product, system and service). Within the concepts of green chemistry and engineering, the replacement of fossil resources with renewables is one of the most prominent and transversal among all the different sectors, as also suggested by the large overall budget of EUR 215.5 million allocated for supporting European R&D activities within the bio-based sector [4]. For example, in transportation, the usage of biofuels (e.g., biodiesel, bioethanol, biomethane, etc.) is increasingly celebrated as one the key strategies to reach 2050 goals. In its 2022 Energy Outlook [5], BP stated that their usage will increase rapidly by achieving a consumption of around 6–7 million barrels/day (equal to 10 EJ/year) within the accelerated and Net Zero scenarios. This trend is mainly driven by fuel usage in aviation (bio-jet fuel) [6,7]. A similar trend was identified by the Organisation for Economic Co-operation and Development (OECD) [8] which showed an increase in biomass consumption up to around 37 Gt in 2060, including food, fuels and materials. Among the latter, bio-polymers represent an outstanding basis for innovative products and technologies: compostable, lighter, designed to reduce the fossil carbon content, etc. The market refers to these kind of bio-commodities (materials and fuels) by the term bio-based chemicals. Among those, some basic bio-molecules (e.g., ethylene, propylene, butadiene, paraxylene, glycerol, methanol, ethanol, etc.) represent the major building blocks on which our society is founded. The market for those bio-products reached 2.4 Mt in 2021 [9], the split among major commodities being represented in Figure 1. The graph also classifies them into two main categories: biodegradable and non-biodegradable. A clear distinction between them is reported in the literature [10]. In general, the term biodegradable is used to identify compounds that may be disposed of through composting and anaerobic digestion [11]. In fact, during these end-of-life (EoL) treatments, biodegradable molecules break down into CO_2, water, CH_4 (in anaerobic digestion), inorganic compounds (nutritional elements) and biomass residues [12–14]. As depicted in Figure 1, the lion's share of the credit is attributed to biodegradable molecules (64.2% on the total).

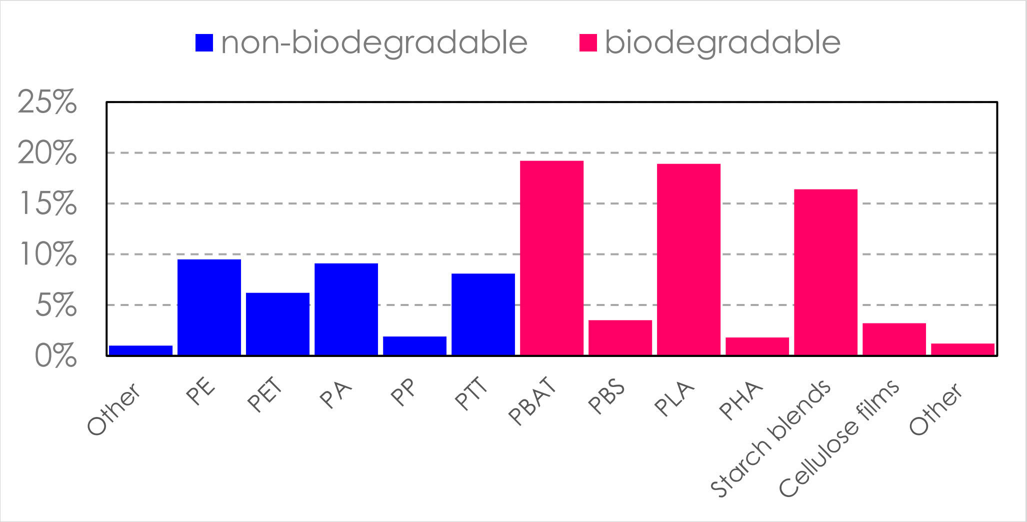

Figure 1. Bio-based chemicals' global production capacity in 2021. Based on [9].

Among these, PBAT (polybutylene adipate terephthalate), PLA (polylactic acid) and Starch blends account for 85% of the class of biodegradables. On the other hand, among the non-biodegradable substances (those that should be mechanically/chemically recycled or thermally valorized during EoL) the principal compounds are polyamides (PAs), polyethylene (PE), polyethylene terephthalate (PET) and polytrimethylene terephthalate (PTT). The full list of abbreviations is reported at the end of the article.

However, in order to be easily affordable, bio-based chemicals should guarantee a lower price than conventional commodity chemicals and consistent production over time. The latter can only be achieved by using a share of dedicated biomasses, so-called primary generation since they originate generally from edible biomasses [15,16]. However, bio-based chemicals could be also synthetized starting from non-edible fractions, such lignocellulosic feedstocks and waste biomasses (second-generation) or algae (third-generation) [15,16].

Despite the possibilities reported above, regarding the usage of second- and third-generation biomasses, a recent study from the European Commission [17] has shown that around 77% of the feedstock used within the 408 investigated bio-refineries are primary biomasses, mainly agricultural feedstock. Unfortunately, cultivated crops require material and energy sources that lead to potential environmental impacts far from being considered negligible or net-zero [18–21]. Among those, land occupation and transformation, as well as contamination, could produce negative repercussions also on a broader scale (e.g., climate change [22]) and on different endpoint receptors (e.g., human health, due to the use of fertilizers [23,24]). Therefore, when possible, a life cycle perspective should be introduced to assess the potentialities of bio-based chemicals derived from dedicated cultivation.

The aim of this article is to provide a short overview of the Life Cycle Assessment (LCA) approach and the most suitable analysis methods available that predict potential impacts on land compartment, as well on other problem-oriented categories. The focus on land issues is due to their importance to ecosystems and the Technosphere. However, impacts on that compartment are not always taken into account during environmental sustainability analyses of bio-products (which are too often focused on climate change only), despite their importance [25]. An application of LCA can guide the synthesis of new chemicals and their market by encouraging the production and purchasing of molecules that have proven lower burdens.

2. Materials and Methods

LCA methodology [26–28] is aimed at evaluating the potential impacts and benefits on the environment of products, processes, systems and organizations. In the case of a product (such as a chemical substance, fuel or material), LCA may cover the entire life cycle (cradle to grave) or part of it (cradle to gate or gate to gate). It depends on the study's goal and its scope (LCA first stage). During this step, the functional unit (FU) shall be defined. FU is a quantitative, measurable and scalable unit that expresses the function of the system. The LCA framework implies a second phase of data collection and modelling (called Life Cycle Inventory or LCI) which is in general the most time-consuming, a third of impact assessment (Life Cycle Impact Assessment—LCIA) and a final stage of interpretation. During LCIA all the input and output flows involved in the production of the studied product or system (i.e., included in the LCI) can be translated into potential environmental problems (midpoint level) or damages on final receptors (e.g., ecosystem quality, human health and resources consumption, the so-called damage-oriented or endpoint level). Results are normalized per the FU; this procedure allows comparison among different products. In the case of bio-based chemicals, literature suggests the adoption of a multi-impact approach by using methodologies able to predict potential burdens on several compartments [29–31]. The adoption of a single-issue approach (e.g., carbon footprint [22]) is not proper for a life cycle assessment study, since the impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied [27,28]. Finally, the interpretation stage implies the LCA results are carefully analyzed to obtain information which supports decision making or the revision of the model created. The LCA structure allows for easy application to different case studies and at different levels of the value chain. In general, it represents a powerful tool for supporting R&D and purchasing activities in the decision to adopt bio-based chemicals from dedicated or waste biomasses [29,31]. Several examples exist related to its application at early design and purchasing stages within each sector of the chemical industry [32]. In particular, focusing on bio-chemicals is relevant to understanding if the usage of waste biomasses (second-generation) is competitive with respect to the exploitation of dedicated cultivations. Figure 2 represents a general overview of the system boundaries for the bio-based sector according with a cradle-to-gate approach. The core process is represented by the biorefinery process (identified as a fermenter in the figure), which leads to the main bio-products (functional unit). In this case, the FU can be fixed as the amount of bio-products generated by a defined time limit, e.g., kg/h or ton/y. Depicted on the left of the figure are the stages involved in the supply chain (upstream) that are responsible for the production of the starting raw material (biomass) and the auxiliaries, which are the energy carriers used in the manufacturing and transportation processes, as well as all emissions and the management of all waste streams generated. In this case, the system boundaries exclude all the downstream stages (usage and EoL of the bio-products). The choice of fixing the boundaries at a cradle to gate analysis is related to the goal and scope. One example is assessing the environmental sustainability of different biomass sources for the same bio-product (e.g., bio-PET). This is represented in Figure 2, where the boundaries differ in terms of the supply chain complexity of the two limited cases described: (a) the exploitation of dedicated biomasses (first-generation) and (b) the use of bio-waste (second-generation). The figure depicts how the use of cultivated biomasses creates several flows upstream which describe soil occupation and exploitation, the production of raw materials and auxiliaries (e.g., seeds and fertilizers) and resources need (e.g., water and diesel for growing). On the other hand, as shown, the usage of waste streams to feed the biorefinery (e.g., biowaste deriving from industries and municipalities) avoids all the flows related to the cultivation and harvesting stages that can be cut off or allocated in part (more conservative scenario). This means a near-zero burden scenario in the upstream stages, since most of the environmental impacts are allocated to the main products (e.g., food, etc.) and not to the bio-product. On the other hand, in the case of the comparison between a biodegradable vs non-biodegradable molecule (e.g., counterposing PLA vs PET for plastic bottles) it is mandatory to extend the boundaries to the downstream processes (cradle to grave) to include the EoL stage that may differ [33]. Therefore, the usage of an LCA approach is always recommended (where possible) for assessing the better choice from an environmental point of view. Focusing on land compartment, the literature [29,34–36] suggests that in some of the cases in which the land use category is investigated, impacts for bio-based products exceed those of their petrochemical counterparts by a factor of ten or more.

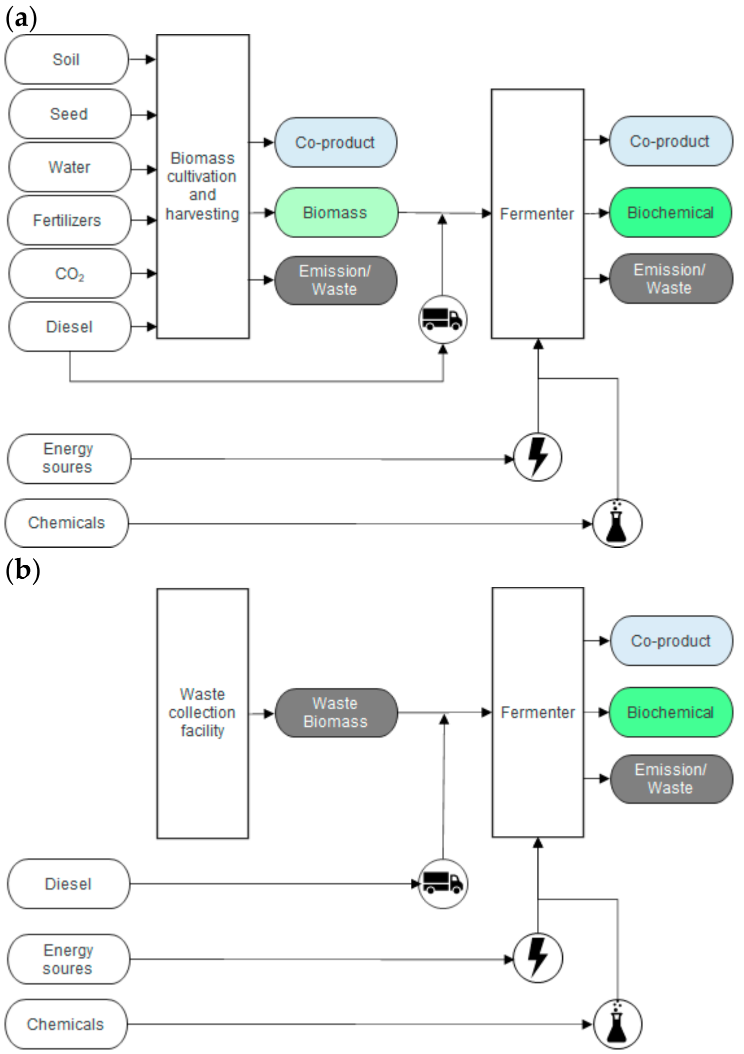

Figure 2. System boundaries for LCA studies of (**a**) bio-based chemicals from dedicated biomass vs (**b**) bio-based chemicals from waste biomass.

In order to complete the LCIA stage and address direct/embodied burdens on land compartment, several analysis methods already exist. In this short article, only some of them are presented and discussed by giving an overview of the possible approaches applicable to support the bio-based sector. In the first part of the manuscript, three methods which follow a multi-impact profile are presented. A multiple-issue approach is proper for a traditional LCA, in accordance with ISO 14044. The model expresses results in terms of different categories permitting study of trends of impacts on different environmental problems at the same time. Table 1 collects them by describing the main characteristics of the three methods selected for discussion. The table summarizes the categories included at the midpoint level (problem-oriented) as well as the geographical extension of each method and the possibility of converting results at the endpoint level (damage-oriented). Categories that influence impact on soil, directly or not, are flagged in orange.

The first method selected is ReCiPe 2016 [23,24]. First released in 2008 [37], it represents a multiple-issue methodology developed by the National Institute of Public Health and Environmental Protection (RIVM), Radboud University, Centrum Milieukunde Leiden (CML) and PRé Sustainability B.V. As depicted in Table 1, ReCiPe 2016 covers 18 impact categories at the midpoint level (problem-oriented) and is also able to classify them into three damage-oriented categories (endpoint level). The method considers several impacts on land compartment. The first one is land use (LU), which is characterized by agricultural land occupation potential (characterization factor), estimated in $m^2 \cdot yr$ (annual crop land) and takes into account the three steps described by Milà i Canals et al. 2007 [38]. The first step is transformation, to make the soil suitable for the next use, then occupation for a certain period. After that, finally, soil relaxation can start (to return the land to a semi-natural state). ReCiPe 2016 also takes into consideration terrestrial acidification potential (TAP, in kgSO_2 eq.), terrestrial ecotoxicity (TETP, in kg 1,4-Dichlorobenzene) and ozone formation in terrestrial ecosystems (OFTE, in kg NO_x eq.).

TAP expresses an estimation of proton (H^+) increase in natural soil as a consequence of the atmospheric deposition of acidifying gases (SO_2, NO_x and NH_3) and of the usage of acid-based fertilizers (sulphur-, nitrogen- and ammonia-based). TETP evaluates the potential effects on the ecosystem due to the leakage of chemical substances with a toxicological effect derived from the large usage of auxiliaries during cultivation stages. OFTE expresses the indirect damages on terrestrial ecosystems as a consequence of the formation of oxidant species in atmosphere. Further details about the method can be found in literature [23,24].

The IMPACT World+ [39] is a globally-regionalized LCIA methodology that constitutes an updated version of previous methods (IMPACT 2002+ [40], LUCAS [41] and EDIP [42]). Similar to ReCiPe 2016, it expresses results in terms of 18 midpoint impact categories (reported in Table 1). Among these, TAP (in kgSO_2 eq.), land transformation, biodiversity and land occupation, biodiversity are the indicators directly connected with the soil compartment and they are all regionalized. Regionalization allows the covering of different levels of spatial resolution to analyze the magnitude of characterization results for each impact category at the global scale and to quantify the relative importance of spatial variability compared to the overall spread of characterization factors [39]. The IMPACT World+ also describes the nexus between land exploitation and negative effects in in terms of loss of biodiversity (the land transformation, biodiversity and land occupation, biodiversity categories), a useful key performance indicator (KPI) when the production plant under study is located near a protected habitat.

The last multi-issue method presented is the EF 3.0 (Environmental Footprint) [43], the methodology recommended by the environmental footprint [44]. In the case of EF 3.0, LCI are converted into 28 midpoint categories listed in Table 1. The EF 3.0 method addresses impacts on land by considering three major categories: *(i)* terrestrial eutrophication potential (TEUP), *(ii)* climate change—land use and land use change and *(iii)* land use. TEUP assesses all the phenomena that lead to an increase of nutrients in soil as a consequence of agricultural practices and is expressed in mol N eq. [45]. Climate change—LU and LU change reflects all carbon emissions and uptakes from carbon stock changes caused by land use change and land use. The category takes into account the effects from direct LU change (i.e., the transformation from one land use type into another in a unique land cover) and indirect LU change (i.e., a certain change in land use or in the use of the feedstock grown on a given piece of land can cause changes in land use outside the system boundary [44]). As stated above, EF 3.0 also includes impacts related to the land use category that describes the use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the LU, the area of land involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the areas affected (changes in soil quality multiplied by the area). The impact category indicator is referred to as the soil quality index, a dimensionless KPI measured in point (Pt) based on Land Use Indicator Value Calculation in Life Cycle Assessment (LANCA®) model and its characterization factor version 2.5 [46–48]. LANCA® model is essentially the result of the aggregation of five different indicators. The first one is erosion potential, which describes the mechanism of soil removal and transportation due to physical phenomena such as rainfall. Then mechanical and physicochemical filtration are indices related to soil permeability. While mechanical filtration describes the quantity of water that can infiltrate a specific soil, physicochemical filtration models the amount of adsorbable cationic pollutants by addressing its capacity to fix and exchange cations. The LANCA® model also considers groundwater regeneration, which assesses the soil's ability to generate groundwater as a consequence of its structure, the surface vegetation and the climatic zone. Finally, biotic production is also considered by the method. It represents the soil's capacity for creating spare biomass.

A further example of analysis method specialized in the assessment of impacts on soil compartment and biogenic products is the True pricing method for agri-food products, developed by True Price and Wageningen Economic Research within the PPS True and Fair Price for Sustainable Products [49,50]. It describes aspects of measuring and valuing the impacts of agri-food products and value chains for categories of land use and change. The method also contains additional information on how effects on biodiversity and ecosystem services (i.e., direct and indirect contributions of ecosystems to human [51]) are accounted for by the true price. The concept of true price is well explained by Galgani et al. [50] as "the sum of the market price (the price at which a product is offered) and the true price gap (the social and environmental costs caused by its production and consumption)". It reflects the negative effects of LU and LU change. For example, the transformation of a natural ecosystem into agricultural land implies the direct degradation of ecosystems, leading to loss of habitats, biodiversity and ecosystem services. In addition, LU for agricultural activities leads to biodiversity loss and has an opportunity cost in terms of ecosystem services. However, the true price index has the capability to measure some benefits over time, translated into a reduction of the social and environmental costs of a product. Therefore, it can be considered a useful sustainability indicator (since it includes economic, societal and environmental aspects) that can assist organizations in identifying improvement opportunities.

Table 1. Comparison between the EF 3.0 [43], the IMPACT World+ [39] and the ReCiPe 2016 [23,24] methods. Land-related categories are highlighted in orange.

EF 3.0 Method		**ReCiPe 2016**		**IMPACT World+**	
midpoint	✔	midpoint	✔	midpoint	✔
endpoint		endpoint	✔	endpoint	✔
geography	European level	geography	Global level	geography	Global level
Impact category at midpoint level	**Unit**	**Impact category at midpoint level**	**Unit**	**Impact category at midpoint level**	**Unit**
Climate change	kg CO_2 eq.	Global warming	kg CO_2 eq.	Climate change, short term	kg CO_2 eq.

Table 1. *Cont.*

EF 3.0 Method		**ReCiPe 2016**		**IMPACT World+**	
Ozone depletion	kg CFC11 eq.	Stratospheric ozone depletion	kg CFC11 eq.	Climate change, long term	kg CO_2 eq.
Ionising radiation	kBq U-235 eq.	Ionizing radiation	kBq Co-60 eq.	Fossil and nuclear energy use	MJ deprived
Photochemical ozone formation	kg NMVOC eq.	Ozone formation, Human health	kg NOx eq.	Mineral resources use	kg deprived
Particulate matter	disease inc.	Fine particulate matter formation	kg PM2.5 eq.	Photochemical oxidant formation	kg NMVOC eq.
Human toxicity, non-cancer	CTUh	Ozone formation, Terrestrial ecosystems	kg NOx eq.	Ozone layer depletion	kg CFC-11 eq.
Human toxicity, cancer	CTUh	Terrestrial acidification	kg SO_2 eq.	Freshwater ecotoxicity	CTUe
Acidification	mol H+ eq.	Freshwater eutrophication	kg P eq.	Human toxicity cancer	CTUh
Eutrophication, freshwater	kg P eq.	Marine eutrophication	kg N eq.	Human toxicity non-cancer	CTUh
Eutrophication, marine	kg N eq.	Terrestrial ecotoxicity	kg 1,4-DCB	Freshwater acidification	kg SO_2 eq.
Eutrophication, terrestrial	mol N eq.	Freshwater ecotoxicity	kg 1,4-DCB	Terrestrial acidification	kg SO_2 eq.
Ecotoxicity, freshwater	CTUe	Marine ecotoxicity	kg 1,4-DCB	Freshwater eutrophication	kg PO_4 eq.
Land use	Pt	Human carcinogenic toxicity	kg 1,4-DCB	Marine eutrophication	kg N eq.
Water use	m^3 depriv.	Human non-carcinogenic toxicity	kg 1,4-DCB	Particulate matter formation	kg PM2.5 eq.
Resource use, fossils	MJ	Land use	m^2 annual crop eq.	Ionizing radiation	Bq C-14 eq.
Resource use, minerals and metals	kg Sb eq.	Mineral resource scarcity	kg Cu eq.	Land transformation, biodiversity	m^2 yr arable
Climate change—Fossil	kg CO_2 eq.	Fossil resource scarcity	kg oil eq.	Land occupation, biodiversity	m^2 yr arable
Climate change—Biogenic	kg CO_2 eq.	Water consumption	m^3	Water scarcity	m^3 world eq.
Climate change—Land use and LU change	kg CO_2 eq.				
Human toxicity, non-cancer—organics	CTUh				
Human toxicity, non-cancer—inorganics	CTUh				
Human toxicity, non-cancer—metals	CTUh				
Human toxicity, cancer—organics	CTUh				
Human toxicity, cancer—inorganics	CTUh				
Human toxicity, cancer—metals	CTUh				
Ecotoxicity, freshwater—organics	CTUe				
Ecotoxicity, freshwater—inorganics	CTUe				
Ecotoxicity, freshwater—metals	CTUe				

3. Results and Discussion

As shown in this short article, there is no unique methodology to address the impact of bio-based chemicals on land when a life cycle perspective is considered. Here some examples were presented, each of them with its peculiarity. The results of the comparison are collected in Table 2.

Table 2. Comparison among land-oriented method and multi-impact approach. Max (★★★) and min (★) score.

	Land-Oriented Method (e.g., LANCA® Model, True Pricing Method for Agri-Food Products, etc.)	**Multi-Impact Approach (e.g., ReCiPe 2016, IMPACT World+, EF 3.0, etc.)**
Assessing different system boundaries (cradle to gate or cradle to grave)	★★★	★★★
Avoid burden-shifting phenomena (e.g., impacts on pre-treatment)	★	★★★
Support non-financial disclosure	★★	★★★
Support environmental impact assessment on land issues	★★★	★
Support eco-design (product, supply chain)	★	★★★
Informative respect to land impacts	★★★	★★
Easy communication (unit of measures)	★★★	★
Barriers for integration with other metrics	★	★

The necessity of extending the evaluation to a wider spectrum of impact categories is generally recommended by literature [29], which confirms the difficulty in making a holistic and comprehensive assessment by considering just one indicator. This is the case with global warming potential, one of the most-used indicators that reflects great variability across different bio-chemicals. A multi-issue approach has several advantages. Among those is the reduction of the likelihood of greenwashing. Expressing results in different impact categories allows the user to expand their knowledge about environmental hotspots. This avoids the burden-shifting phenomenon which can occur when few indicators are used or in case the analysis does not include all the life cycle stages involved. This is particularly useful when a comparison study is performed to identify if a bio-based chemical is more sustainable from an environmental point of view relative to its fossil fuel-based counterpart. This approach is particularly recommended when a dedicated biomass is used, since it helps the reader to understand all the potential impacts related to all direct exploitation of resources for the cultivation phase (e.g., fertilizers), as well as the indirect burdens associated with infrastructure (e.g., bio-refinery plant) and for all the auxiliary sources included (e.g., production of energy vectors used in transportation, such as bio-diesel). However, the multiple-impact approach is also recommended when waste biomass is used as raw material. It is useful to identify if all the recovery and purification steps needed to transform the waste stream into a valuable starting substrate make the exploitation of the waste stream still competitive if compared with dedicated biomasses or fossil fuel-based counterparts. Plenty of examples exist in literature that advise following this multi-criteria analysis [52–55].

This kind of approach may be also used for rethinking the supply chain of a company. According to the European directive [56], some enterprises need to disclose all the non-financial information that reflect how the organization operates inside and out its boundaries in terms of environmental, social and ethical commitment. When the bio-based sector is under investigation, the company may ask the tier 1 and 2 suppliers to provide data useful for meeting the description in term of soil quality, occupation and transformation. These KPIs, together with other indices (e.g., carbon [22] and water footprint [57]), are adopted to juxtapose several vendors and select those which disclose the lowest contribution. In this context all the methods here presented are useful. However, in case the enterprise has to provide information on other impacts rather just those on land compartment, the multi-impact approaches (e.g., ReCiPe 2016, IMPACT World+ and EF 3.0) can be more suitable for integrating the analysis.

On the other hand, when the impacts on land have been identified as prominent, the adoption of the LANCA® model or the true pricing index is recommended. This could be the case when, according to the materiality analysis, the organization has identified soil stewardship as one of the most prominent material themes to be addressed after a stakeholder engagement. Another example in which LCA results can assist in the final decision is environmental impact assessment (EIA) [58]. EIA is a predictive tool, necessary to identify environmental hotspots of a project before its formal acceptance. In the case of EIA, the life cycle assessment is not compulsory, but can be used to support authorization activities on projects related to agriculture and forestry, as well as the construction of a new biorefinery production plant (in particular when they are close to protected habitat). In this situation, the two land-oriented models can improve communication by producing data on technical fields connected to soil quality (erosion potential, mechanical and physicochemical filtration, groundwater regeneration and biotic production), biodiversity and ecosystem services. These results can be shared with officers and local stakeholders during open consultation activities to allow for a better understanding of the environmental issues and favor project acceptance.

As explained at the beginning, the aim of this work is just informing the readers about the existence of some alternatives and, when applicable, guiding them in the selection of the most appropriate methods to assess the bio-based sector. A single right choice does not exist, since it will be influenced by the goal and scope of the study that may differ case by case.

However, each approach has its own drawbacks. If from one side the adoption of several impact indicators assists the decision maker in displaying a detailed environmental profile of product under study, the final results are more suitable for a business to business (B2B) communication. Understanding a product/system eco-profile needs technical skills and familiarity with the LCA methodology not always common to consumers (B2C) or to office workers of the purchasing business unit. On the other hand, to avoid burden-shifting and support the eco-design of products and supply chains, a multi-criteria analysis is always recommended.

4. Conclusions

In conclusion, when bio-chemicals are under early design study, the application of a life cycle perspective is possible and recommended for identifying hotspots and potentialities with respect to their counterparts. LCA may be adopted as a scientific methodology to address potential environmental impacts, such as the repercussions on land compartment. These are strictly suggested when dedicated cultivation is used as raw materials, due to the extensive usage of fertilizers and resources (e.g., water during irrigation and diesel for harvesting). Several stand-alone LCIA methods were presented: some more oriented to the land issue (LANCA® and the true pricing index models); other classified as multi-impact approaches (ReCiPe 2016, IMPACT World+ and EF 3.0).

The adoption of a multi-impact approach is recommended in order to obtain results regarding several ecosystem compartments, as well as resources and human health. However, its adoption to communicate results is challenging: greater uncertainty (in particular for some toxicological categories and for the endpoint level), major difficulties in figure interpretation (not easily understandable units of measure) and troubles in weighting to identify the most relevant category. On the other hand, models like LANCA® return a well-detailed technical insight on soil without any other information on the rest.

Therefore, no strict procedure exists to guide practitioners in their selection. As a general rule of thumb, a combined application of multiple methods allows for a wider overview of the main problems, with the possibility of combining the results for further confirmation. However, the adoption of further methodologies is more time- and cost-consuming, in particular during the interpretation stage.

An ulterior limitation of the LCA approach is the possibility of obtaining results before the products are marketed. This represents a barrier, due to corporate knowhow and the most predominant usage of the LCA methodology for ex-post evaluations. Hopefully, a broad, widespread understanding of the environmental footprint methodology [44] will enable companies within the EU and their association categories to work together in the process of reviewing and populating public databases with high-quality data. On the other hand, there is the necessity to move toward an ex ante LCA analysis [59] able to predict the burdens of bio-chemicals even if with some uncertainties.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data used in the discussion are available in the references reported in section below.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

B2B	Business to Business
B2C	Business to Consumer
CML	Centrum Milieukunde Leiden
EDIP	Environmental Design of Industrial Products
EIA	Environmental Impact Assessment
EoL	End of Life
ISO	International Organization for Standardization
LANCA	Land Use Indicator Value Calculation in Life Cycle Assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land use
LUCAS	(LCIA method Used for a Canadian-Specific context
OECD	The Organisation for Economic Co-operation and Development
OFTE	Ozone formation, terrestrial ecosystems
PA	Polyamide(s)
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoate(s)
PLA	Polylactic acid
PP	Polypropylene
PTT	Polytrimethylene terephthalate
RIVM	National Institute of Public Health and Environ-mental Protection
TAP	Terrestrial acidification potential
TETP	Terrestrial ecotoxicity potential
TEUP	Terrestrial eutrophication potential

References

1. Anastas, P.T.; Warner, J. *Green Chemistry: Theory and Practice*; Oxford University Press: Oxford, UK, 1998.
2. Cespi, D.; Esposito, I.; Cucciniello, R.; Anastas, P.T. Beyond the beaker: Benign by design society. *Curr. Res. Green. Sustain. Chem.* **2020**, *3*, 100028. [CrossRef]
3. Anastas, P.T.; Zimmerman, J.B. Design through the 12 principles of green engineering. *Env. Sci. Tech.* **2003**, *37*, 94–101. [CrossRef]
4. Circular Bio-Based Europe Joint Undertaking Annual Work Programme 2023. Available online: https://www.cbe.europa.eu/news/cbe-ju-sets-funding-priorities-2023 (accessed on 21 April 2023).
5. BP p.l.c. *bp Energy Outlook 2022*; BP p.l.c.: London, UK, 2022. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2022.pdf (accessed on 21 April 2023).
6. Shahabuddin, M.; Tanvir Alam, M.; Krishna, B.B.; Bhaskar, T.; Perkins, G. A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. *Bioresour. Technol.* **2020**, *312*, 123596. [CrossRef]
7. O'Lenick, A.J. Guerbet Chemistry. *J. Surfactants Deterg.* **2001**, *4*, 311–315. [CrossRef]

8. The Organisation for Economic Co-Operation and Development (OECD). *Global Material Resources Outlook to 2060—Economic Drivers and Environmental Consequences*; OECD Publishing: Paris, France, 2018. Available online: https://www.oecd.org/publications/global-material-resources-outlook-to-2060-9789264307452-en.htm (accessed on 21 April 2023).
9. European Bioplastics e.V. *Bioplastics: Facts and Figures*; European Bioplastics: Berlin, Germany, 2021. Available online: https://docs.european-bioplastics.org/publications/EUBP_Facts_and_figures.pdf (accessed on 21 April 2023).
10. Hairon Azhar, N.N.; Ang, D.T.-C.; Abdullah, R.; Harikrishna, J.A.; Cheng, A. Bio-Based Materials Riding theWave of Sustainability: Common Misconceptions, Opportunities, Challenges and the Way Forward. *Sustainability* **2022**, *14*, 5032. [CrossRef]
11. Quecholac-Piña, X.; Hernández-Berriel, M.d.C.; Mañón-Salas, M.d.C.; Espinosa-Valdemar, R.M.; Vázquez-Morillas, A. Degradation of Plastics under Anaerobic Conditions: A Short Review. *Polymers* **2020**, *12*, 109. [CrossRef]
12. Stoica, M. Biodegradable Nanomaterials for Drink Packaging. In *Nanotechnology in the Beverage Industry*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 609–632.
13. Folino, A.; Karageorgiou, A.; Calabrò, P.S.; Komilis, D. Biodegradation of Wasted Bioplastics in Natural and Industrial Environments: A Review. *Sustainability* **2020**, *12*, 6030. [CrossRef]
14. Kale, G.; Kijchavengkul, T.; Auras, R.; Rubino, M.; Selke, S.E.; Singh, S.P. Compostability of Bioplastic Packaging Materials: An Overview. *Macromol. Biosci.* **2007**, *7*, 255–277. [CrossRef]
15. Lee, R.A.; Lavoie, J.-M. From first- to third-generation biofuels: Challenges of producing a commodity from a biomass of increasing complexity. *Anim. Front.* **2013**, *2*, 6–11. [CrossRef]
16. Moodley, P. Sustainable biofuels: Opportunities and challenges. In *Applied Biotechnology Reviews, Sustainable Biofuels*; Ramesh Ray, C., Ed.; Academic Press: Cambridge, MA, USA, 2021; pp. 1–20.
17. Baldoni, E.; Reumerman, P.; Parisi, C.; Platt, R.; González Hermoso, H.; Vikla, K.; Vos, J.; M'barek, R. *Chemical and Material Driven Biorefineries in the EU and Beyond*; JRC124809; Publications Office of the European Union: Luxembourg, 2021.
18. Zuiderveen, E.A.R.; Kuipers1, K.J.J.; Caldeira, C.; Hanssen, S.; van der Hulst, M.; de Jonge, M.M.J.; Vlysidis, A.; van Zelm, R.; Sala, S.; Huijbregts, M.A.J. The potential of emerging bio-based products to reduce environmental impacts. *Nat. Portf.* **2022**, preprint. [CrossRef]
19. Papong, S.; Malakul, P.; Trungkavashirakun, R.; Wenunun, P.; Chom-In, T.; Nithitanakul, M.; Sarobol, E. Comparative assessment of the environmental profile of PLA and PET drinking water bottles from a life cycle perspective. *J. Clean. Prod.* **2014**, *65*, 539–550. [CrossRef]
20. Leejarkpai, T.; Mungcharoen, T.; Suwanmanee, U. Comparative assessment of global warming impact and eco-efficiency of PS (polystyrene), PET (polyethylene terephthalate) and PLA (polylactic acid) boxes. *J. Clean. Prod.* **2016**, *125*, 95–107. [CrossRef]
21. Suwanmanee, U.; Varabuntoonvit, V.; Chaiwutthinan, P.; Tajan, M.; Mungcharoen, T.; Leejarkpai, T. Life cycle assessment of single use thermoform boxes made from polystyrene (PS), polylactic acid, (PLA), and PLA/starch: Cradle to consumer gate. *Int. J. Life Cycle Assess.* **2013**, *18*, 401–417. [CrossRef]
22. *14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. International Organization for Standardization (ISO): Geneva, Switzerland, 2018.
23. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. ReCiPe 2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
24. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.D.M.; Hollander, A.; Zijp, M.; van Zelm, R. *ReCiPe 2016—A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level*; Report I: Characterization; National Institute for Public Health and the Environment (RIVM): Utrecht, The Netherlands, 2017. Available online: https://pre-sustainability.com/legacy/download/Report_ReCiPe_2017.pdf (accessed on 21 April 2023).
25. Bishop, G.; Styles, D.; Lens, P.N.L. Environmental performance comparison of bioplastics and petrochemical plastics: A review of life cycle assessment (LCA) methodological decisions. *Resour. Conserv. Recy.* **2021**, *168*, 105451–105465. [CrossRef]
26. *14040:2006/Amd 1:2020*; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization (ISO): Geneva, Switzerland.
27. *14044:2006/Amd 1:2017*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines—Amendment 1. ISO: Geneva, Switzerland. Available online: https://www.iso.org/standard/72357.html (accessed on 21 April 2023).
28. *14044:2006/Amd 2:2020*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines—Amendment 2. ISO: Geneva, Switzerland. Available online: https://www.iso.org/standard/76122.html (accessed on 21 April 2023).
29. Ögmundarson, Ó.; Herrgård, M.J.; Förster, J.; Hauschild, M.Z.; Fantke, P. Addressing environmental sustainability of biochemicals. *Nat. Sustain.* **2020**, *3*, 167–174. [CrossRef]
30. *EN 16760:2015*; Bio-Based Products—Life Cycle Assessment. European Committee for Standardisation: Brussels, Belgium, 2015.
31. Cespi, D.; Passarini, F.; Vassura, I.; Cavani, F. Butadiene from biomass, a life cycle perspective to address sustainability in the chemical industry. *Green Chem.* **2016**, *18*, 1625–1638. [CrossRef]
32. Cespi, D.; Passarini, F.; Neri, E.; Cucciniello, R.; Cavani, F. LCA integration within sustainability metrics for chemical companies. In *Life Cycle Assessment in the Chemical Product Chain*, 1st ed.; Maranghi, S., Brondi, C., Eds.; Springer: Cham, Switzerland, 2020; Chapter 3; pp. 53–73.
33. Gironi, F.; Piemonte, V. Life Cycle Assessment of Polylactic Acid and Polyethylene Terephthalate Bottles for Drinking Water. *Environ. Prog. Sustain.* **2011**, *30*, 459–468. [CrossRef]

34. Daful, A.G.; Haigh, K.; Vaskan, P.; Görgens, J.F. Environmental impact assessment of lignocellulosic lactic acid production: Integrated with existing sugar mills. *Food Bioprod. Process.* **2016**, *99*, 58–70. [CrossRef]
35. Patel, M.; Crank, M.; Dornburg, V.; Hermann, B.; Roes, L.; Hüsing, B.; Overbeek, L.; Terragni, F.; Recchia, E. Medium and Long-Term Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources—The Potential of White Biotechnology. Thre BREW Project. 2006. Available online: https://edepot.wur.nl/183326 (accessed on 21 April 2023).
36. Hermann, B.G.; Blok, K.; Patel, M.K. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change. *Environ. Sci. Technol.* **2007**, *41*, 7915–7921. [CrossRef]
37. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; van Zelm, R. *ReCiPe 2008—A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level*, 1st ed.; Version 1.08; Ministry of Housing, Spatial Planning and the Environment (VROM): The Hague, The Netherlands, 2013.
38. Milà i Canals, L.; Bauer, C.; Depestele, J.; Freiermuth Knuchel, R.; Gaillard, G.; Michelsen, O.; Müller-Wenk, R.; Rydgren, B. Key Elements in a Framework for Land Use Impact Assessment Within LCA. *Int. J. Life Cycle Assess.* **2007**, *12*, 5–15. [CrossRef]
39. Bulle, C.; Margni, M.; Patouillard, L.; Boulay, A.M.; Bourgault, G.; De Bruille, V.; Cao, V.; Hauschild, M.; Henderson, A.; Humbert, S.; et al. IMPACT World+: A globally regionalized life cycle impact assessment method. *Int. J. Life Cycle Assess.* **2019**, *24*, 1653–1674. [CrossRef]
40. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A new life cycle impact assessment methodology. *Int. J. Life Cycle Assess.* **2003**, *8*, 324–330. [CrossRef]
41. Toffoletto, L.; Bulle, C.; Godin, J.; Reid, C.; Deschênes, L. LUCAS—A new LCIA method used for a Canadian-specific context. *Int. J. Life Cycle Assess.* **2007**, *12*, 93–102. [CrossRef]
42. Hauschild, M.Z.; Wenzel, H. *Environmental Assessment of Products. Scientific Background*; Kluwer Academic Publishers: Hingham, MA, USA, 1998; Volume 2.
43. European Platform on Life Cycle Assessment. Available online: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml (accessed on 21 April 2023).
44. European Commission. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. Available online: https://environment.ec.europa.eu/system/files/2021-12/Commission%20Recommendation%20on%20the%20use%20of%20the%20Environmental%20Footprint%20methods_0.pdf (accessed on 21 April 2023).
45. Seppälä, J.; Posch, M.; Johansson, M.; Hettelingh, J.P. Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. *Int. J. Life Cycle Assess.* **2006**, *11*, 403–416. [CrossRef]
46. Bos, U.; Horn, R.; Beck, T.; Lindner, J.P.; Fischer, M. *LANCA® Characterization Factors for Life Cycle Impact Assessment—Version 2.0*; Fraunhofer IBP: Stuttgart, Germany, 2016.
47. De Laurentiis, V.; Secchi, M.; Bos, U.; Horn, R.; Laurent, A.; Sala, S. Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *J. Clean. Prod.* **2019**, *215*, 63–74. [CrossRef] [PubMed]
48. Horn, R.; Maier, S. LANCA®-Characterization Factors for Life Cycle Impact Assessment, Version 2.5. 2018. Available online: http://publica.fraunhofer.de/documents/N-379310.html (accessed on 21 April 2023).
49. Galgani, P.; Woltjer, G.; de Adelhart Toorop, R.; de Groot Ruiz, A.; Varoucha, E. Land Use, Land Use Change, Biodiversity and Ecosystem Services. True Pricing Method for Agri-Food Products. 2021. Available online: https://edepot.wur.nl/555581 (accessed on 21 April 2023).
50. Galgani, P.; van Veen, B.; Kanidou, D.; de Adelhart Toorop, R.; Woltjer, G. True Price Assessment Method for Agri-Food Products. 2023. Available online: https://edepot.wur.nl/585906 (accessed on 21 April 2023).
51. Kumar, P. *TEEB: The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*; Routledge: London, UK; Washington, DC, USA, 2010.
52. Patel, A.D.; Meesters, K.; den Uil, H.; de Jong, E.; Bloka, K.; Patel, M.K. Sustainability assessment of novel chemical processes at early stage: Application to biobased processes. *Energy Environ. Sci.* **2012**, *5*, 8430–8444. [CrossRef]
53. Cespi, D.; Cucciniello, R.; Ricciardi, M.; Capacchione, C.; Vassura, I.; Passarini, F.; Proto, A. A simplified early stage assessment of process intensification: Glycidol as a value-added product from epichlorohydrin industry wastes. *Green Chem.* **2016**, *18*, 4559–4570. [CrossRef]
54. Tripodi, A.; Bahadori, E.; Cespi, D.; Passarini, F.; Cavani, F.; Tabanelli, T.; Rossetti, I. Acetonitrile from Bioethanol Ammoxidation: Process Design from the Grass-Roots and Life Cycle Analysis. *ACS Sustain. Chem. Eng.* **2018**, *6*, 5441–5451. [CrossRef]
55. Cok, B.; Tsiropoulos, I.; Roes, A.L.; Patel, M.K. Succinic acid production derived from carbohydrates: An energy and greenhouse gas assessment of a platform chemical toward a bio-based economy. *Biofuels Bioprod. Bioref.* **2014**, *8*, 16–29. [CrossRef]
56. Directive 2014/95/EU of The European Parliament and of The Council of 22 October 2014 amending Directive 2013/34/EU as Regards Disclosure of Non-Financial and Diversity Information by Certain Large Undertakings and Groups. Available online: https://eur-lex.europa.eu/legal-content/EN/NIM/?uri=CELEX%3A32014L0095 (accessed on 21 April 2023).
57. *14046:2014*; Environmental Management—Water Footprint—Principles, Requirements and Guidelines. International Organization for Standardization (ISO): Geneva, Switzerland, 2014.

58. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the Assessment of the Effects of Certain Public and Private Projects on the Environment Text with EEA Relevance. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0052 (accessed on 21 April 2023).
59. Tecchio, P.; Freni, P.; De Benedetti, B.; Fenouillot, F. Ex-ante Life Cycle Assessment approach developed for a case study on bio-based polybutylene succinate. *J. Clean. Prod.* **2016**, *112*, 316–325. [CrossRef]