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Evaluation of Abiotic Resource LCIA Methods

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Abstract: In a life cycle assessment (LCA), the impacts on resources are evaluated at the area of protection (AoP) with the same name, through life cycle impact assessment (LCIA) methods. There are different LCIA methods available in literature that assesses abiotic resources, and the goal of this study was to propose recommendations for that impact category. We evaluated 19 different LCIA methods, through two criteria (scientific robustness and scope), divided into three assessment levels, *i.e.*, resource accounting methods (RAM), midpoint, and endpoint. In order to support the assessment, we applied some LCIA methods to a case study of ethylene production. For RAM, the most suitable LCIA method was CEENE (Cumulative Exergy Extraction from the Natural Environment) (but SED (Solar Energy Demand) and ICEC (Industrial Cumulative Exergy Consumption)/ECEC (Ecological Cumulative Exergy Consumption) may also be recommended), while the midpoint level was ADP (Abiotic Depletion Potential), and the endpoint level was both the Recipe Endpoint and EPS2000 (Environmental Priority Strategies). We could notice that the assessment for the AoP Resources is not yet well established in the LCA community, since new LCIA methods (with different approaches) and assessment frameworks are showing up, and this trend may continue in the future.

Keywords: abiotic; resource; life cycle assessment; LCA; life cycle impact assessment; LCIA; method; Brazil

1. Introduction

Natural resources are essential for our society, either for provision, supporting, regulating or cultural services [1]. However, due to the world population growth, together with the increase in the consumption per capita and poor resource management, we are being led to a sustainability crisis. Natural resources may be classified in several ways, (a) renewable or non-renewable, (b) stocks, funds or flows, (c) biotic or abiotic, among other classifications [2]. Regarding the latter, biotic resources are those that come from living organisms, while abiotic resources are the result of past biological processes (e.g., crude oil) or chemical processes (e.g., metal).

One of the tools that may assist in sustainable resource management, at the industrial scale, is a Life Cycle Assessment (LCA). Resources are seen in two ways in an LCA: (1) In one way, they are the inputs needed in industrial processes for the production of a product, and in this sense they are evaluated at the life cycle inventory (LCI) stage; and (2) in another way, they are evaluated as an area of protection (AoP), in life cycle impact assessments (LCIAs), *i.e.*, natural resources are one type of environmental impact assessed, and there are different methods to evaluate these impacts.

According to traditional classifications [2,3], these methods may be categorized into three groups: (1) Resource accounting methods (RAM), which make a more simplified impact analysis, focused mainly on grouping the resources into single score indicators, as energy or mass; (2) Midpoint resource depletion methods, that go beyond RAM, evaluating impacts related to resource depletion due to its use, as the use-to-availability ratio; and (3) Endpoint resource depletion methods, that go even beyond the previous group, taking into account the consequences of resource depletion, in many cases, through backup technology [4,5], e.g., evaluating the extra effort (energy or cost) needed to extract less economically feasible resources.

Due to the lack of consensus in the LCA community regarding impacts on natural resources, there are other approaches of how the LCIA methods evaluate that AoP. Rorbech *et al.* [6] classified LCIA methods into three groups: (1) Methods that account for the consumption of limited resources, which rather evaluate the resource competition and assume that they are exchangeable (as RAM); (2) Methods that evaluate the depletion of resources, which may be subdivided into midpoint and endpoint (and according to the authors would better represent the AoP Resources); and (3) Methods that evaluate the extra effort needed in the future due to actual resource extraction (e.g., Recipe Endpoint), which according to the authors do not represent a specific AoP as Resources, but are midpoint impacts that affect other AoPs (human health and natural environment). Dewulf *et al.* [7] suggested new AoPs for LCA and Life Cycle Sustainability Assessment (LCSA), proposing five perspectives: (P1) the safeguard subject is the resource itself; (P2) the concern is the capacity of this resource to generate provisional services; (P3) the safeguard subject is the capacity of this resource to generate other ecosystem services; (P4) where consequential aspects are considered, e.g., socioeconomic mechanisms are taken into account; and (P5) the concern is human well-being, giving a rather holistic perception by grouping all previous perspectives. The authors also mention that P4 and P5 go beyond classical LCA, and would better fit in LCSA.

Even though there are different ways of grouping LCIA methods in LCA, and how they affect (different) AoPs, in this manuscript we used the rather traditional overview, proposed by ILCD (International Reference Life Cycle Data System) and Swart *et al.* [2,3] (Figure 1). In this sense, there are some studies that already critically evaluated different LCIA methods, for instance, Liao *et al.* [8] evaluated thermodynamic-based RAM, and pointed out the Cumulative Exergy Extraction from the Natural Environment (CEENE) [9] and the Solar Energy Demand (SED) [10], as the recommended LCIA methods for that approach. In ILCD [3], where different LCIAs were evaluated in order to make recommendations for the European context, the Abiotic Depletion Potential (ADP) [11], adapted to the reserve base (Reserve base, according to the USGS (United States Geological Survey), accounts for all reserves that have the actual potential of extraction and may be economically viable in the future. The ADP method originally considered the ultimate reserve, which would be the amount of a certain resource in the Earth's crust), was recommended for midpoint assessment, while there was no recommendation for endpoint LCIA methods. The Life Cycle Initiative, from UNEP-SETAC (United Nations Environment Programme and the Society for Environmental Toxicology and Chemistry), is an ongoing project to create a worldwide consensus on recommendations of LCIA methods (http://www.lifecycleinitiative.org/activities/phase-i/life-cycle-impact-assessment-programme/) [12] which may be considered as a step forward to what has been done by ILCD [3].

Due to the variety of LCIA methods available in literature and the complexity in choosing one for an LCA study, there is a demand by LCA practitioners for support in decision making in private and public organizations. Therefore, the Brazilian Life Cycle Impact Assessment Network (Rede de Pesquisa em Avaliação do Ciclo de Vida, RAICV, 2014), (Regimento da Rede de Pesquisa em Avaliação de Impacto do Ciclo de Vida. São Bernardo do Campo, 11 November 2014, RAICV) evaluated different LCIA methods, for several impact categories, including Abiotic Resources. Nevertheless, due to certain characteristics from the Abiotic Resources category (e.g., a relative site-generic impact), the results for this category may be applied to other countries as well. As will be seen later, some RAM create characterization factors (CF) for both biotic and abiotic resources; thus, in some cases the recommendation went beyond abiotic resources (for RAM). Therefore, the objective of this manuscript was to evaluate different operational LCIA methods for (abiotic) resources available in literature in order to propose a recommendation .To facilitate the assessment, we applied some of these operational LCIA methods to a case study of ethylene production in Brazil through bio-based and fossil-based routes.

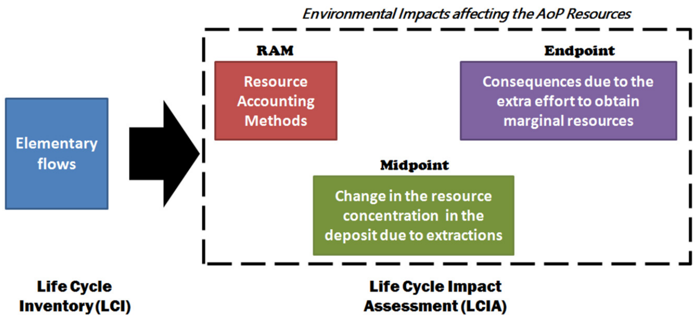

Figure 1. Simplified representation of cause-effect on AoP Resources, based on traditional LCIA groupings proposed by ILCD [3] and Swart *et al.* [2]

2. Results and Discussion

2.1. Operational Resource-Based LCIA Methods

For the evaluation of the LCIA methods, we adopted the classification according to ILCD [3] and Swart *et al.* [2], *i.e.*, in three levels of impact assessment (Figure 1): RAM, midpoint, and endpoint methods. In total, we found 19 operational LCIA methods, which are described and assessed below. The values for each LCIA method can be seen in Table 1 (for RAM), Table 2 (for midpoint), and Table 3 (for endpoint).

2.1.1. Resource Accounting Methods (RAM)

CED

The Cumulative Energy Demand (CED) [13] is one example of an operational LCIA method for quantifying the cumulative energy use, which was introduced in the 1970s by Boustead and Hancock [14] and Pimentel *et al.* [15], and standardized by VDI (the Association of German Engineers) [16]. It is an RAM that uses the heating value of materials as an aggregation unit. Frischknecht *et al.* [17] evaluated several operational LCIA methods with this approach, pointing out some differences among them, such as the use of high or low heating values. The CED can also be used as a proxy in LCA, since it presented a direct correlation with several other LCIA indicators [18,19], especially for the fossil energy category. Generally, CED (and similar methods) accounts solely for the resources that have a certain energy or heating value, which may be seen as a limitation of the approach because it becomes restricted to energetic resources (fossil, nuclear, solar, geothermal, wind, and hydropower) and biomass. It is not a regionalized method, but according to Alvarenga [20], spatial-differentiation may be considered for land use if an adaptation is previously performed to avoid double-counting with biomass, as suggested in Alvarenga *et al.* [21]. Since it uses energy, based on the first law of thermodynamics, the scientific robustness is not so high since there are other LCIA methods that use the second law of thermodynamics, which has a higher scientific robustness (see below). Further, since it has CF entirely for energy resources and biomass (and site-generic), the CED had low scores for both criteria.

CExD

The Cumulative Exergy Demand (CExD) [22] is a RAM that uses the CED as a baseline, but instead of using energy as the indicator, it uses exergy. Exergy of a resource or system is the maximum amount of useful work that can be obtained from it [23]. By using exergy, the CExD is able to account for several types of resources (fossil, nuclear, wind, solar, potential, biomass, water, metals, and minerals), including those with no heating value. Land use is not accounted for in order to avoid double-counting with biomass. This method does not have spatial-differentiated CF, but according to Alvarenga [20], it may be adapted to consider the regionalization for land use (as in CED). Dewulf *et al.* [9] and Swart *et al.* [2] mentioned several inconsistencies in the CExD model to calculate the exergy value of metals, minerals, and biotic resources. Since CExD uses exergy (2nd law of thermodynamics), it has a higher scientific robustness than CED and a higher amount of CF. Therefore, it had a medium score (higher than CED) for the criteria evaluated.

CEENE

The CEENE method [9] is a RAM that tries to aggregate different types of resources in a single unit (exergy). It considers several elementary flows, with a higher number of CF than other RAM that use the same approach (e.g., CExD). Moreover, it is seen as an evolution of CExD, and by using exergy instead of energy, it has a higher scientific robustness than CED. Liao *et al.* [8] considered CEENE as (one of) the best thermodynamic-based LCIA method(s). One of the differences between CEENE and CExD is the approach used to account for the exergy of metals and minerals and for biotic resources (biomass and/or land use). CEENE 1.0 does not have spatially-differentiated CF; however, in CEENE 2.0 (There is an even more recent version (3.0), where there is also spatial-differentiation for ocean occupation (e.g., for aquaculture), but it was not considered since it was published after 2014), there is spatial-differentiation for land use through the work of Alvarenga *et al.* [21]. In this case, CF are presented in different scales (see in below). Due to the advance in the model to calculate exergy for some resources, CEENE has a higher score for scientific robustness than CExD and higher number of CF. Further, CEENE 2.0 has regionalized CF for land use. Therefore, CEENE had the highest score for both criteria, in comparison to other RAM.

SED

The Solar Energy Demand (SED), developed by Rugani *et al.* [10], is a RAM that uses the Emergy concept [24] as a baseline. In Emergy, the cradle of an LCA is not in the boundary between the ecosphere and anthroposphere, as considered by several RAM (e.g., CEENE), but within the limits of the geobiosphere, *i.e.*, the Sun, tidal energy, and geothermal energy, aggregated into an indicator called solar energy equivalent [2]. In this LCIA method, the authors focused on creating a high amount of CF through the compilation of several published works that had quantified the transformities (Transformity is the name give in Emergy scientific community to what is called as CF in LCA community) of different natural resources. Regarding the possible double-counting between biotic resources and land use, SED follows the approach of CEENE, which chooses to account for land use (in contrary to CED and CExD); therefore, we can say that SED and CEENE are equivalent in this aspect. As previously mentioned, SED has a high number of CF, but they are not regionalized. Emergy is an approach that is still challenged by the scientific community, even though there are some efforts to solve some of the problems and align it to LCA [25,26], in which SED was a result of that effort. Due to those reasons, SED received a medium-high score for both criteria.

MIPS

Material Inputs Per Service (MIPS) [27,28] is an indicator of the cumulative amount of resources of product/service through its life cycle, and sometimes is called a Material Footprint. MIPS is based on material flow analysis, separating materials in five classes: abiotic resources, biotic resources, earth movement, water, and air [28]. As some other RAM, MIPS was developed outside of LCA and later it was considered as an LCIA method. Saurat and Ritthoff [29] proposed a method to calculate CF for ecoinvent database v2.2. However, the CF are not fully made available in that publication, while the authors mention that the CF are a beta version and the new CF shall be available in Wuppertal Institute website in the future. Even though in Ritthouff *et al.* [28] and in Saurat and Ritthoff [29], the possibility and implementation of regionalization is mentioned, this is in fact a regionalization of LCI, and not LCIA as in CEENE 2.0. Therefore, MIPS does not have regionalized CF. Saurat and Ritthoff [29] and Wiesen *et al.* [30] mentioned some differences between traditional MIPS assessment and LCA and the need for adaptation of MIPS into an ecoinvent database, as the lack of elementary flows from unused extracted materials from mining. Due to those reasons, MIPS received a medium-low score for scientific robustness and a medium score for scope.

LREx

The Exergy-based accounting for land resource (LREx) [21] is a method focused on accounting for land use as a natural resource through exergy, and is proposed to be complementary to the CEENE method. Regarding the issue of avoiding double-counting in biotic resources in RAM, LREx suggests to account for the biomass extracted, when this originally occurs in a natural environment, and for the land use, when originally changed in a man-made environment, and in this case, based on natural potential net primary production (NPP). Regarding the latter, it has spatial-differentiated CF in different scales, *i.e.*, site-generic (world), continent-based, country-based, region-based (for six countries), and on a grid scale (approximately 10 km $\times$ 10 km). In this sense, LREx had a high scientific robustness, but a low score for scope, even though it was regionalized, since it was focused solely on land use and biotic resources. In fact, LREx is a specific LCIA method for a type of elementary flow (land use); thus, it is proposed to be used as complementary to other RAM, and not as a single indicator.

ICEC/ECEC

The Industrial Cumulative Exergy Consumption/Ecological Cumulative Exergy Consumption (ICEC/ECEC) is an LCIA method developed by Hau e Bakshi [31] and Zhang *et al.* [32], based on exergy. The method has CF that are operational for extended input-output databases, as USA Input-Output Database 1997, while other LCIA methods (previously mentioned) are operational for process-based LCI (e.g., ecoinvent). First, the authors tried to operationalize the cumulative exergy consumption (CExC), proposed by Szargut [33], via the ICEC. However, this method also proposes an additional approach, filling the gap between LCA and economic assessment of natural resources (evaluating ecosystem services), via the ECEC [32]. For the latter, it used principles from Emergy [24], allowing for consideration of the exergy consumption of ecological goods and services in solar energy equivalents. Therefore, ECEC has a similar approach to SED, where the cradle is at the boundary of the geobiosphere. Even though ICEC/ECEC tries to include ecosystem services, this inclusion is still limited for some important ones, as pollination and carbon sequestration. Moreover, ICEC/ECEC does not have regionalized CF. Nevertheless, ECEC proposes some solutions for emergy critical aspects, such as allocation. For those reasons, ICEC/ECEC had a medium-high score for both criteria.

EF

The Ecological Footprint (EF) is defined as the area of water and land needed to directly and indirectly support a certain population [34]. It divides these areas in six classes: crop land, forest, pasture, water, infrastructure, and energy (carbon sequestration). For LCA, EF of a product may be defined by the area directly and indirectly needed during the life cycle of this product. EF was operationalized as an LCIA method by Huijbregts *et al.* [35], where it was also added (through some adaptations) to the area needed for nuclear resources. EF appeared to be a good proxy, but it was not recommended for mineral-based products or those with high particulate matter emission [35]. It may be interpreted as complementary to CED/CExD, making it possible to account for land use with low uncertainty, but for that, some adaptations are needed to avoid double counting with biotic resources. EF may be regionalized for different scales, based on specific biocapacities, but there is no operational LCIA method with spatially-differentiated CF. On the other hand, EF (as an LCIA method) only considers elementary flows related to fossil and nuclear resources, land use, and CO_2 emission. Therefore, it has a limited scope (it does not account for metals and minerals), and goes beyond the AoP Resources by accounting for CO_2 emissions. For these reasons, the final score of this RAM was rather low.

Table 1. Quali-quantitative assessment of the LCIA methods at the RAM level for the AoP Resources.

LCIA Method	CEENE	CExD	CED	SED	MIPS	LREx	ICEC/ECEC	EF
Base reference	[9]	[22]	[13,16]	[10]	[28]	[21]	[31,32]	[34,35]
Criterion #1 (Scope)	5	3	1	4	3	1	4	3
Criterion #2 (Scientific robustness)	5	3	2	4	2	5	4	2
Final score	5.0	3.0	1.5	4.0	2.5	3.0	4.0	2.5
Observation	We evaluated v1.0 and v2.0	-	-	-	-	Specific for land use	-	-

2.1.2. Midpoint LCIA Methods

ADP

Abiotic Depletion Potential (ADP) was initially developed by Guinée [11], was later modified in van Oers *et al.* [36], and included in the LCIA methodology CML-IA (from the Institute of Environmental Sciences (CML), named CML-IA). To calculate CF, ADP uses an equation that involves the extraction rate of a certain resource and the squared of the availability of this resource in deposits. All resources are normalized to the CF of antimony (Sb); therefore, the indicator is Sb equivalent (Sb-eq). Regarding the deposits used to calculate the CF, original ADP used the ultimate reserves, which may be defined as the total amount of a certain substance (e.g., iron) available in the Earth's crust, oceans and atmosphere. In this sense, the ultimate reserve also includes deposits that are not economically or technically feasible for extraction. Later, ADP created CF for other approaches as well, *i.e.*, for reserve base and economic reserves. ADP has CF for metals and minerals, and the total amount of CF is dependent on the approach used (ultimate reserve, reserve base or economic reserve). For fossil fuels, ADP also has CF, but in the latter versions of the ultimate reserve approach (e.g., v4.2), the CF are based on the net heating value of the fossil fuel, similar to CED (a RAM), thus not providing a midpoint resource depletion assessment. ADP has high scientific robustness in LCA community, and the approach based on the reserve base is recommended by ILCD [3] as the LCIA method to be used for midpoint assessment. Furthermore, the amount of CF provided by this method is quite high in comparison to other depletion LCIA methods, despite the approach considered. In this sense, ADP received high scores for the criteria considered.

EDIP

EDIP (Environmental Design of Industrial Products) 1997/2003 [37] is an LCIA methodology established in the LCA community and traditionally used for the assessment of products. This LCIA methodology considers several impact categories, including the depletion of resources, with CF for metals, minerals, and fossil fuels. For this category, the CF are calculated by an equation that exclusively involves the amount of available resources in deposits, *i.e.*, not considering the extraction rate, as in ADP. Therefore, the property of a resource for having a high/low extraction rate is not accounted for by the CF. For this reason, EDIP received a lower score than ADP in the criterion scientific robustness. The deposits considered in this LCIA method are based on the economic reserves. EDIP has a high amount of CF for the resources previously mentioned, higher than Recipe Midpoint [38], but slightly lower than ADP (depending on the approach used). For that reason, EDIP had a medium-high score for scope.

Recipe Midpoint

Recipe Midpoint (Recipe has two versions (midpoint and endpoint) and, regarding resource depletion, there are differences in the analysis. For this reason they were evaluated separately.) [39] has CF for fossil fuels, metals and minerals, and the approach used is different for the types of resources. For fossil fuels, Recipe Midpoint considers the heating value, *i.e.*, a RAM approach, similar to CED. For metals and minerals, the approach is different, considering the depletion of those resources at midpoint level. Recipe Midpoint has an innovative approach, in comparison to ADP and EDIP, evaluated through the deposits of minerals, and not by the metals *per se*. According to the authors, by doing this, the LCIA method better represents the reality of the metals' geological distribution, allowing them to cover a higher number of commodities, especially those extracted as by-products. This method considers the change in the ore grade, *i.e.*, the decrease in the concentration of minerals in an ore due to extraction. Recipe Midpoint has less CF than ADP and EDIP, and this is probably due to the higher complexity level to obtain the data needed to create the CF by the approach from the former. Further, Recipe Midpoint has some inconsistencies in the creation of CF [40] (e.g., allocation procedure). For those reasons, this method had a medium score for both criteria.

ORI

ORI (Ore Requirement Indicator) [40] is a specific LCIA method for the evaluation of metal and mineral depletion; therefore, it does not have CF for fossil fuels, for instance. It uses a similar approach to Recipe Midpoint, *i.e.*, considers the change in ore grade, and its equation is the reciprocal of the ore grade variation, thus the change in ore mass by mass of metal extracted. However, instead of using a small database (locally or temporally) to generate CF, as performed in Recipe Midpoint, the authors use a more robust database that has information from different mines for more than a decade. In order to guarantee scientific soundness, the authors created CF solely for the metals in which the source from the database represented more than 50% of worldwide production. In this way, it has a higher scientific robustness than Recipe Midpoint. On the other hand, it had a limited number of CF (9 metals). ORI has an interesting approach, indicating an option to be followed for midpoint assessment, especially with the expansion of data for metals and minerals. However, since it has solely 9 CF and is focused on metals and minerals (no CF for fossil fuels), it has a low operationalization for LCA (later this LCIA method may be enhanced by the inclusion of more CF), and as a consequence, it had a low score for scope and a high score for scientific robustness.

AADP

The Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) [41] may be considered a complementary method for the ADP, by including the depletion assessment resources that have already been extracted from their deposits and are now available in the anthroposphere (e.g., landfill), bringing an innovative concept. However, due to the difficulty of obtaining consistent data, it has CF for solely 10 metals. Since it is a specific LCIA method for metals, it does not have CF for fossil fuels. For those reasons, it had a high score for scientific robustness and a low score for scope, as ORI. AADP went through some adaptations, where more CF were created (35 in total), but this new version [42] was not considered in this study because it was published after December 2014.

OGD

The Ore Grade Decrease (OGD) was proposed by Vieira *et al.* [43], and it has a similar approach to ORI, *i.e.*, it evaluated the ore grade change due to extraction of metals, based on a geologic distribution model. For this reason, it has a high scientific robustness, but the authors created only one CF, for copper, giving a low score for the scope criterion. In order to differentiate this from other low-scoring LCIA methods at the scope criterion (ORI and AADP), we gave an even lower score for OGD.

Table 2. Quali-quantitative assessment of the LCIA methods at midpoint level for the AoP Resources.

LCIA Method	ADP	EDIP	Recipe Midpoint	ORI	AADP	OGD
Base reference	[11,36]	[37]	[39]	[40]	[41]	[43]
Criterion #1 (Scope)	5	4	3	1	1	0.5
Criterion #2 (Scientific robustness)	4	3	3	5	5	5
Final score	4.5	3.5	3.0	3.0	3.0	2.75
Observation	-	-	-	Specific for metals	Specific for metals at anthroposphere	Since it had only one CF

2.1.3. Endpoint LCIA Methods

Eco-Indicator 99

Eco-Indicator 99 is an LCIA endpoint method, *i.e.*, it evaluates the final impact from using fossil fuels, metals and minerals by the approach proposed in Muller-Wenk [4], which considers the increased (future) workload in the extraction of more inaccessible reserves resources (e.g., marginal reserves). In Eco-indicator 99, the surplus energy (MJ_{se}) is used as an aggregated unit for resource depletion [44]. This resource depletion characterization model is used in other LCIA methodologies as well, such as in TRACI (the Tool for the Reduction and Assessment of Chemical and other environmental Impacts), BEES (Building for Environmental and Economic Sustainability), and Impact 2002+ [13]. The base for the Eco-indicator 99 assessment is through the estimated surplus energy required for the extraction of minerals, based on the decline of the concentration rate in time [4,45]. The analysis uses geostatistical models to indicate the distribution structure, quantity and quality of the minerals and the future effort needed, to calculate the surplus energy for extraction of resources. Following the same trend from other endpoint LCIA methods, the Eco-indicator 99 has fewer CF than midpoint LCIA methods. In addition, compared to other endpoint LCIA methods (e.g., Recipe Endpoint and EPS2000), the number of CF is also lower, and with the absence of important minerals in the global context, such as gold, iron, palladium, molybdenum, lead and platinum. For this reason, the score for scope was medium. On one hand, the characterization model is part of different methods LCIA (e.g., Impact 2002+), which are consolidated and accepted by the scientific community, but on the other hand, the characterization models was based (for metals) on a limited number of low accuracy curves. Therefore, Eco-indicator 99's scientific robustness was considered medium-low, in comparison to other endpoint LCIA methods.

Recipe Endpoint

Recipe Endpoint [39] assesses the depletion of fossil fuels, metals and minerals through another approach (compared to its midpoint version), going beyond the cause-effect relationship, *i.e.*, to an endpoint level [2,3]. The approach, somewhat similar to the Eco-indicator 99, evaluates the increase in the cost of extracting those resources due to their depletion, thus using the approach proposed by Müller-Wenk [4] and Stewart and Weidema [5]. Because it is an LCIA method that goes beyond the cause and effect of resource depletion impacts, it has greater complexity of data to create CF, and in this sense, it has fewer CF than midpoint LCIA methods (e.g., ADP). Moreover, when compared to other endpoint LCIA methods, it has more CF than the Eco-indicator 99, for instance. For metals and minerals, CF were calculated based on extraction costs and on the CF of Recipe Midpoint. Therefore, the endpoint CF also has the same calculation inconsistencies mentioned in Swart and Dewulf [40] (e.g., allocation procedure). Regarding fossil fuels, the CF for crude oil was based on data from the International Energy Agency, assuming constant annual production over time, using a limited relationship of price and production and determining an arbitrary time period [46]. Additionally, due to a lack of data, coal and natural gas CF were calculated using extrapolated data from crude oil. Thus, the Recipe Endpoint received a medium-high score for the scope criterion and a medium score for the scientific robustness criterion.

EPS2000

The Environmental Priority Strategies (EPS) is an endpoint LCIA method, proposed for the first time in 1990, and it was later modified; the final version is named EPS2000 [47,48]. The principle for damage assessment is through the willingness-to-pay (WTP) approach, in which natural resources and environmental impacts are put in monetary values. One of the impact categories is named abiotic stock resource (or depletion of reserves), which evaluates the depletion impacts (at endpoint level) from metals, minerals and fossil resources. The unit used is the Environmental Load Unit (ELU), which represents the costs of sustainable extraction of non-renewable resources. Considering the limitations of WTP for abiotic resources, EPS2000 proposes a market scenario, in which the production costs of a certain substance are used to estimate the CF for resource depletion. The characterization models from EPS are not entirely transparent, considering that they are based on political and sociocultural values. Therefore, EPS2000 had a medium-low score for scientific robustness. The current version of EPS2000 has a significant amount of CF, higher than other endpoint LCIA methods (e.g., Recipe Endpoint), and for this reason it received a high score for scope. As a consequence, EPS2000 received the same final score from Recipe Endpoint.

SuCo

The Surplus Cost (SuCo) method, proposed in Ponsioen *et al.* [46], aims to adapt or integrate elementary flows related to fossil resources to LCA. Therefore, this LCIA method is specific for that type of resource, not generating CF for metals and minerals (amongst other resource types). The proposal from SuCo is to assess fossil resource scarcity based on the future increase in global costs due to the use of marginal fossil resources used in the life cycle of products. Therefore, SuCo follows the same trend as Eco-indicator 99 and Recipe Endpoint. In practice, SuCo may be seen as an evolution from Recipe Endpoint (which may be seen as an evolution from Eco-indicator 99), and that there is a possibility to incorporate SuCo to Recipe Endpoint in the next versions of the latter [49]. SuCo has CF for three types of fossil fuels (crude oil, natural gas, and coal), from which it used specific data for the calculation of the respective resource. Therefore, it has higher scientific robustness than Recipe Endpoint, in which only data from crude oil was used. For that reason, it received a medium-high score for that criterion. Since it is a specific LCIA method for fossil fuels, it received a low score for scope.

Exergoecology

Exergoecology, proposed by Valero e Valero [50,51], brings an innovative approach to the LCA community, where the authors try to quantify the depletion of metals and minerals through the exergy cost, which, in a simplified way, would be to make a cumulative exergy consumption assessment, but in the opposite direction, *i.e.*, from grave-to-cradle. The main idea is that the method quantifies the exergy needed to let the metal be ready for extraction through mining, from its reference state (where exergy is zero). This method may be considered as evaluating the AoP Resources at the endpoint level, since it considers the consequences from resource depletion. Exergoecology has an interesting alternative approach, but it is not yet completely operational for LCA, mainly for two reasons: (1) Through the published articles, we were able to quantify only seven CF; and (2) this originates from a scientific area that needs more research, and more CF should be generated. Regarding the latter reason, even though exergy is already established in LCA, the scientific proposal from Valero and Valero [50,51] goes beyond traditional exergy, *i.e.*, they propose accounting for the exergy from grave-to-cradle. For those reasons, Exergoecology received a low score for scope and a medium-high score for scientific robustness.

Table 3. Quali-quantitative assessment of the LCIA methods at the endpoint level for the AoP Resources.

LCIA Method	Eco-Indicator 99	Recipe Endpoint	EPS2000	SuCo	Exergoecology
Base reference	[44]	[39]	[47,48]	[46]	[50,51]
Criterion #1 (Scope)	3	4	5	1	1
Criterion #2 (Scientific robustness)	2	3	2	4	4
Final score	2.5	3.5	3.5	2.5	2.5

2.2. Case Study

We applied an ethylene production case study to some of the aforementioned LCIA methods. We compared the traditional fossil-based ethylene (FE) to the bioethanol-based ethylene (BE), produced from sugarcane. From the 19 different LCIA methods, 13 were selected to be applied in the case study. Six LCIA methods were excluded due to the lack of operational CF. The LREx method was applied via the CEENE v2.0 method. Further, it is interesting to note that some LCIA methodologies (Impact 2002+, BEES, and TRACI) are indirectly considered in this study since they use a similar characterization model as Eco-indicator 99. It may be important to mention that the LCIA method Ecological Scarcity [52] was not considered in the case study, nor in the previous theoretical assessment, because it is a Swiss-based distance-to-the-target method, and is not in the scope of the Brazilian context. For ADP, we used three versions in the assessment of better evaluation: (1) ADP v3.2, an older version of ADP that accounts for metals, minerals, and fossil fuels in Sb-eq, through the ultimate reserves (thus midpoint assessment); (2) ADP v4.2, a newer version of ADP that accounts for metals and minerals as Sb-eq, through ultimate reserves, while for fossil fuels it accounts for the low heating value (thus similar to a RAM); and (3) ADP-ILCD, an ADP version that assesses metals, minerals and fossil fuels as Sb-eq through a reserve base.

2.2.1. RAM

For all five RAM methods, the results showed BE with higher environmental impacts than FE, as can be seen in Figure 2. For the CED, CExD, CEENE v2.0, and SED, FE had approximately half of the total value of BE (varying between 47% and 54%). On the other hand, FE had approximately 34% of the total value of BE for the CEENE method v1.0. The main hotspots found in each of the RAM methods are discussed below.

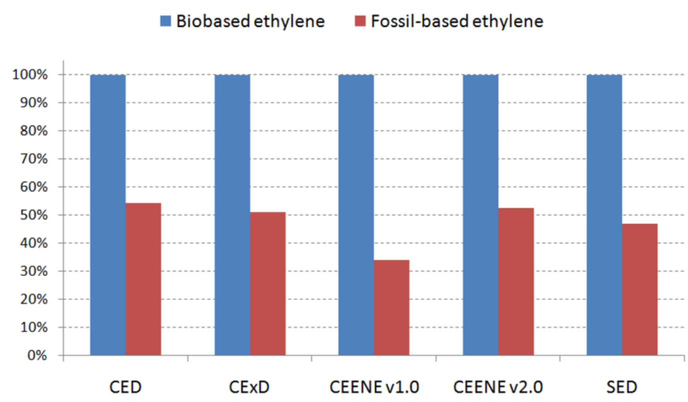

Figure 2. Resource-based assessment of bio-based ethylene and fossil-based ethylene, with different RAM methods, normalized to the highest value

CED and CExD had similar results, *i.e.*, BE had greater environmental impact, mainly due to the energy content of the sugarcane (86%–87%), and a considerable fraction of the total value was due to fossil energy consumption (10%–11%), mainly due to natural gas consumed during ethanol-to-ethylene production and diesel consumed in the sugarcane stage. For the FE, most of the environmental impacts were due to the crude oil (63%–64%) and natural gas (31%–33%) consumption in the ethylene supply chain. An interesting difference between CED and CExD was the results for water resources, *i.e.*, for CED, water resources were consumed mainly due to hydropower (potential energy), while the CExD accounted not only for water from hydropower (potential energy), but water was also used in the ethanol production process.

For the CEENE method, BE environmental impacts were mainly due to land occupation for the sugarcane cultivation (90% in v1.0 and 85% in v2.0). Fossil fuels also had a significant contribution in the total value (7% in v1.0 and 11% in v2.0), and from that approximately 53% was due to natural gas consumption in the ethanol-to-ethylene production process and 22% was due to diesel consumption during sugarcane cultivation. The main difference between v1.0 and v2.0 was land occupation, *i.e.*, while the former uses average European solar irradiation as a proxy, giving a higher result, the latter uses regionalized data on natural potential NPP as a proxy (which for this case study, gave a lower value).

When using the SED, BE had more than double the total environmental impacts, and the main hotspot was the consumption of gypsum (mineral) in the sugarcane stage, which was responsible for more than 66% of the total environmental impact. After that, the consumption of limestone (mineral), with 10% of total, natural gas in the ethanol-to-ethylene process (4%), and diesel at the sugarcane stage (3%) were also relevant contributors for the SED. Regarding the FE, most of the environmental impacts were due to crude oil (67%) and natural gas (26%) consumed in the ethylene supply chain. Sodium chloride had also a relevant share of contribution (3%) for FE.

It is interesting to note that for FE, the results among the five RAM showed similar hotspots. On the other hand, while for CED, CExD, CEENE v1.0 and CEENE v2.0, the main hotspot for BE was the sugarcane (either as a biomass or the land occupation for its cultivation); in SED the land occupation impacts accounted for only 2% of the total environmental impacts, and the minerals consumed during the sugarcane stage were the main hotspots. This is due to the different approach used in SED, which sets the geobiosphere as system boundaries to create the CF, while the former four RAM set the boundary between the ecosphere and the anthroposphere [2,21].

2.2.2. Midpoint

For the midpoint level, the results were slightly divergent among the LCIA methods (Figure 3). For ADP v3.2, ADP v4.2, and the Recipe Midpoint, BE was the most beneficial option for the environment, with values of approximately 20%–30% of the environmental impact of FE. On the other hand, ADP-ILCD, EDIP2003, ORI and AADP had opposite results, and the degree of how beneficial FE was varied considerably. The main reason was the higher importance given to metals and minerals in the latter LCIA methods. The relevance of the elementary flows for each LCIA method can be better visualized in Table 4, Figures 4 and 5.

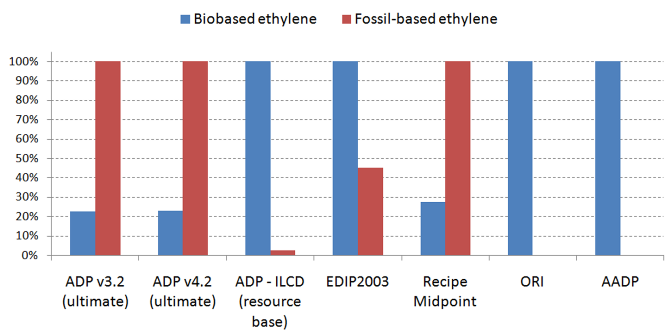

Figure 3. Resource-based assessment of bio-based ethylene and fossil-based ethylene, with different midpoint LCIA methods, normalized to the highest value.

Table 4. Relative contribution of specific elementary flows for bio-based ethylene (BE) and fossil-based ethylene (FE) at the midpoint and endpoint LCIA methods considered in this case study.

Elementary Flows (Natural Resources)	**ADP v3.2 (Ultimate)**		**ADP v4.2 (Ultimate)**		**ADP-ILCD (Res. Base)**		**EDIP2003**		**Recipe Midpoint**		**ORI**		**AADP**		**Eco-Indicator 99**		**Recipe Endpoint**		**EPS2000**	
	BE	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**	**BE**	**FE**
Metals and minerals																				
Chromium	-	-	-	-	-	-	-	-	2%	-	-	-	-	-	-	-	1%	-	2%	-
Copper	-	-	2%	-	4%	-	7%	-	4%	-	34%	28%	-	-	1%	-	2%	-	13%	-
Iron	-	-	-	-	-	-	-	-	6%	-	-	-	-	1%	-	-	2%	-	2%	-
Lead	-	-	1%	-	30%	-	12%	-	-	-	1%	1%	-	1%	-	-	-	-	7%	-
Nickel	-	-	-	-	4%	-	35%	-	3%	-	57%	61%	89%	92%	1%	-	1%	-	14%	-
Uranium	-	-	-	-	-	49%	-	8%	-	1%	-	-	-	-	-	-	-	-	-	-
Phosphate rock	-	-	-	-	1%	-	-	-	-	-	-	-	-	-	-	-	-	-	3%	-
Zinc	-	-	2%	-	58%	-	23%	-	-	-	1%	-	2%	-	-	-	-	-	14%	-
Fossil fuels																				
Crude oil (diesel-cane)	20%	-	21%	-	-	-	2%	-	14%	-	-	-	-	-	23%	-	22%	-	5%	-
Crude oil (FE)	-	36%	-	34%	-	28%	-	59%	-	66%	-	-	-	-	-	66%	-	66%	-	51%
Crude oil (other)	8%	-	8%	-	-	-	1%	-	11%	-	-	-	-	-	9%	-	8%	-	3%	-
Natural gas (BE)	54%	-	51%	-	-	-	5%	-	40%	-	-	-	-	-	55%	-	50%	-	25%	-
Natural gas (FE)	-	62%	-	65%	-	15%	-	32%	-	32%	-	-	-	-	-	34%	-	32%	-	49%
Natural gas (other)	8%	-	7%	-	-	-	1%	-	6%	-	-	-	-	-	8%	-	7%	-	4%	-
Hard coal	6%	-	4%	-	-	-	-	-	4%	-	-	-	-	-	-	-	4%	-	-	-
Other elementary flows	4%	2%	6%	1%	3%	8%	14%	1%	10%	1%	7%	10%	9%	6%	4%	0%	5%	2%	8%	0%

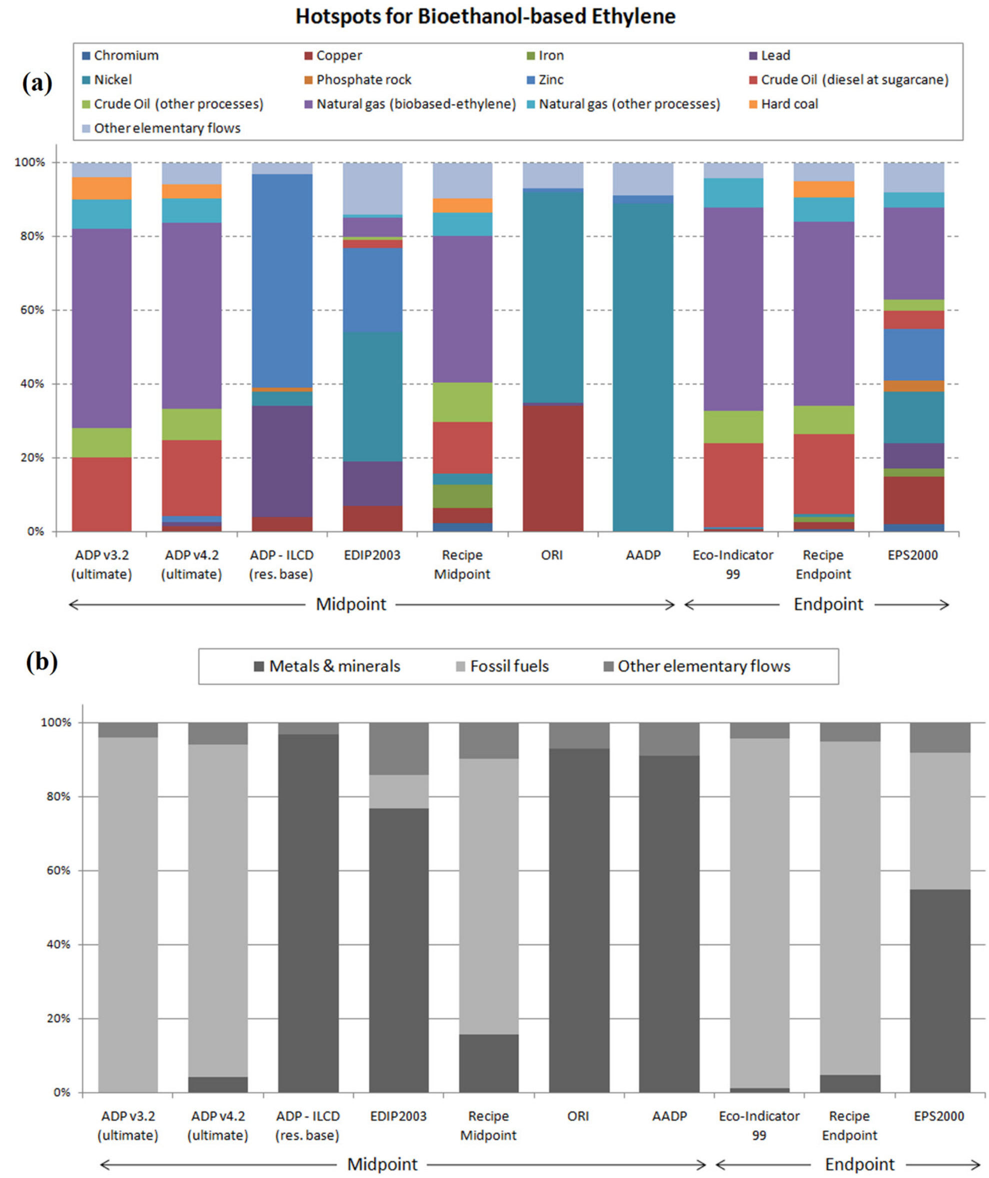

Figure 4. Hotspots from bioethanol-based ethylene with respect to (**a**) elementary flow level; and (**b**) type of resource level for midpoint and endpoint LCIA methods.

For the two versions of ADP that consider the ultimate reserve as background data for CF (v3.2 and v4.2), fossil fuels seemed to be much more relevant than metals and minerals. As a consequence, FE had worse results, and the main driver for that was the consumption of crude oil (62% for ADP v3.2 and 65% for ADP v4.2) and natural gas (36% for ADP v3.2 and 34% for ADP v4.2) at the ethylene supply chain. Meanwhile, for BE, the main hotspots were also fossil fuels, *i.e.*, natural gas consumed at the ethanol-to-ethylene process (54% of the environmental impacts in both methods) and crude oil consumed as diesel at the sugarcane stage. On the other hand, ADP-ILCD, which considers the reserve base approach, seemed to give more importance to metals and minerals, putting BE as the product with the highest environmental impacts, from which zinc, lead, copper, and nickel, mainly used in the production of agricultural machinery, were the main hotspots for BE. Meanwhile, due to the approach considered (reserve base), fossil fuels used in the agricultural stage had a minor contribution. For FE, uranium (This is a limitation of the study; the ecoinvent dataset was used for FE, which is European-based, thus has Uranium is an important energy source for electricity), natural gas and crude oil were the main hotspots, all of which were consumed in the ethylene supply chain (Table 4, Figures 4 and 5).

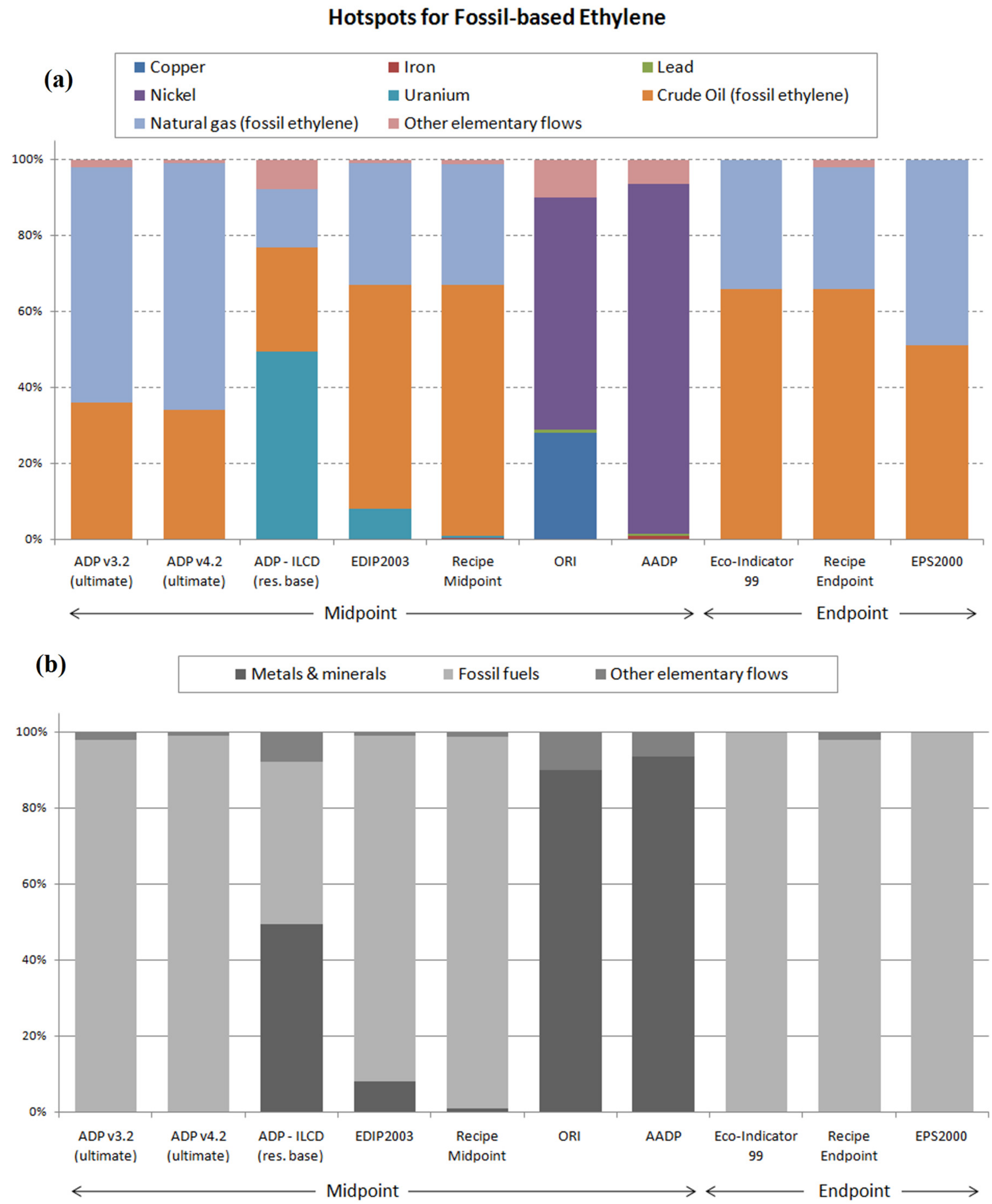

Figure 5. Hotspots from fossil-based ethylene with respect to (**a**) elementary flow level; and (**b**) type of resource level for midpoint and endpoint LCIA methods.

Similar to ADP v3.2 and v4.2, the Recipe Midpoint also gave more importance to fossil fuels (after normalization), identifying FE as the product with the highest environmental impacts. Crude oil (66%) and natural gas (32%) consumed in the ethylene supply chain were the main hotspots for FE. The main hotspots for BE were natural gas (46%) and crude oil (25%), consumed in several processes. Moreover, some metals also had a considerable contribution to BE, especially chromium, copper, iron, and nickel (summing to 15% of the environmental impacts), mainly used in the production of agricultural and industrial machinery (Table 4, Figures 4 and 5).

EDIP 2003 seemed to give more importance to metals and minerals, probably due to the economic reserve approach. BE was the product with the highest environmental impacts, mainly due to nickel, zinc, lead, and copper (total of 77%), primarily used in the production of agricultural and industrial machinery. Similar to ADP-ILCD, fossil fuels used in the agricultural stage had minor contributions. The main hotspots for FE were crude oil (59%) and natural gas (32%) consumed in the ethylene supply chain (Table 4, Figures 4 and 5).

Regarding ORI and AADP, BE was the product with the highest environmental impacts, since these methods have CF solely for metals and minerals thus far. In AADP, BE was highly influenced by nickel (89%), while in ORI it was mainly influenced by nickel (57%) and copper (34%). The same metals were the main hotspots for FE, showing that a low number of CF may indicate a misleading interpretation (if we consider the results from the other midpoint LCIA methods). In this sense, it is important to mention that these LCIA methods may be currently used in LCA with caution, *i.e.*, it should be complemented by other LCIA methods for other types of resources (e.g., fossil fuels), and avoid making a joint overall abiotic resource assessment.

From the results at the midpoint level, we could see that certain LCIA methods gave more focus to metals and minerals, as those considering a reserve base (ADP-ILCD) and an economic reserve (EDIP2003) as the background approach for creating CF. This is probably due to the lower amount of metal deposits available in higher concentrations. Meanwhile, ADP versions considering the ultimate reserves (v3.2 and v4.2) and the Recipe Midpoint gave more focus to fossil fuels. Furthermore, we could notice that using LCIA methods with a low amount of CF, such as ORI and AADP, may show inconsistent results, especially for products highly based on fossil fuels (as FE). Therefore, this case study highlights the importance of the criterion assessing the number of reference flows with CF, when dealing with abiotic resource depletion. In this sense, it is important to highlight that a possible procedure to choose an LCIA method is to make a preliminary environmental impact assessment, finding possible hotspots (e.g., iron may be a hotspot when performing an LCA of industrial machinery), and then making sure that the chosen LCIA method has CF for those elementary flows.

2.2.3. Endpoint

For the endpoint LCIA methods, the results of the case study were more convergent than the midpoint LCIA methods, *i.e.*, they all considered the BE as more beneficial to the environment (Figure 6).

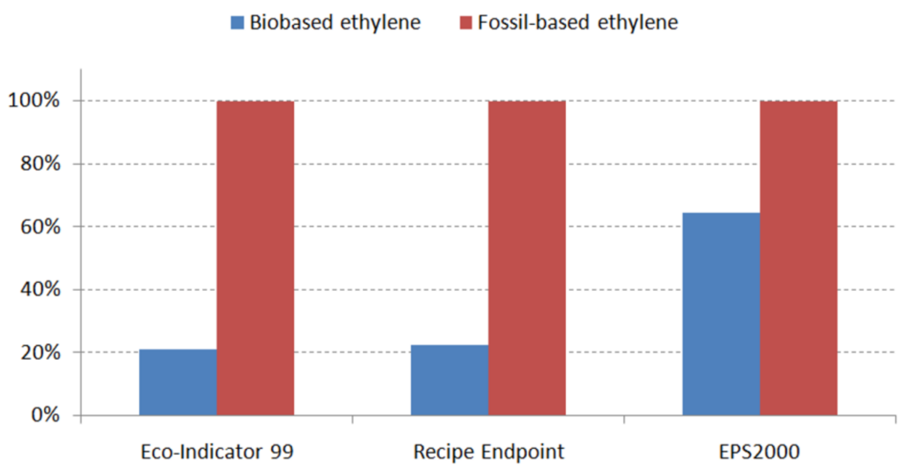

Figure 6. Resource-based assessment of bio-based ethylene and fossil-based ethylene, with different endpoint LCIA methods, normalized to the highest value.

For the Eco-indicator 99, the environmental impacts from FE were mainly due to crude oil (66%) and natural gas (34%) consumed in the ethylene supply chain. Thus, the environmental impacts from metals and minerals were negligible. Meanwhile, for the BE, 63% of the environmental impacts were due to overall natural gas consumption (87% of those in the ethanol-to-ethylene process), 32% due to crude oil consumption (72% of those due to diesel in the sugarcane stage), 1% from copper and 1% from nickel, both mainly due to agricultural machinery (Table 4, Figures 4 and 5).

The Recipe Endpoint had similar results as the Eco-indicator 99, *i.e.*, crude oil (66%) and natural gas (32%) consumed in the ethylene supply chain were the main hotspots for FE. For BE, the main hotspots were natural gas and crude oil, but some metals (chromium, copper, iron, and nickel) also had a significant contribution to the environmental impacts (Table 4, Figures 4 and 5).

The method EPS2000, which uses a different approach from the Recipe Endpoint and Eco-indicator 99, indicated different hotspots for BE. Natural gas and crude oil in different processes contributed to approximately 37% of the impacts, while several metals (chromium, copper, iron, lead, nickel, phosphate rock, and zinc) contributed to approximately 55% of the impacts (Table 4, Figures 4 and 5). For FE, the results were more similar to the other endpoint LCIA methods, *i.e.*, crude oil and natural gas consumed in the ethylene supply chain were the main hotspots.

2.2.4. Discussion

Liao *et al.* [8] analyzed different LCIA methods in a case study of titania produced in China through different routes (chloride and sulphate). Even though the products analyzed were quite different from our study, some results were similar among the RAM methods, showing that CED, CExD and CEENE were mainly influenced by fossil resources (since titania is not a bio-based product), while SED was mainly influenced by metals and minerals. Moreover, for the endpoint LCIA methods considered in Liao *et al.* [8], the results also highlight a higher contribution of fossil fuels for the Eco-indicator 99, in comparison to the EPS2000, which also had a significant contribution of metals. Therefore, Liao *et al.* [8] can corroborate our findings in both approaches (RAM and Endpoint).

Robech *et al.* [6] compared different resource-based LCIA methods by applying them to 2744 market datasets from the ecoinvent database. The results showed that the ADP (ultimate reserves), the Eco-indicator 99, and the Recipe Endpoint were mainly influenced by fossil fuels, while EDIP2003, ADP-ILCD and EPS2000 were mainly influenced by metals and minerals, corroborating the results of this study; except for EPS2000, which may have to do with the products analyzed, *i.e.*, our product system may be more fossil influenced than the averaged 2744 product systems analyzed by Robech *et al.* [6]. Further, even though our case study was still mainly influenced by fossil fuels in the EPS2000, the share of contribution was lower than the Recipe Endpoint and the Eco-indicator 99. For the RAM methods of Robech *et al.* [6], SED showed many more contributions to metals and minerals than CEENE v1.0 and CExD, validating the results of this study at the RAM level as well.

Moreover, similar results were found in the case study between the ADP (v3.2 and v4.2) and the Eco-indicator 99, identifying BE as the better option with approximately 20%–22% of the impacts from FE; this can be verified by the high correlation between these two LCIA methods found in Berger *et al.* [53]. Meanwhile, the similar results from our case study between ADP-ILCD and EDIP2003 (BE as the worst option), and among Eco-indicator 99, ADP (v4.2 and v3.2), and the Recipe Endpoint (BE as the best option) can also be corroborated by the high correlation found by Robech *et al.* [6] among those LCIA methods.

Klinglmair *et al.* [38] compared the CF of different resource-based LCIA methods, normalized with respect to iron, showing that ADP (It was not clear which version they used, but it seemed to be a version considering the ultimate reserve approach) has a higher relative CF for crude oil than other metals, confirming the results of this case study, and is mainly influenced by fossil fuels in ADP v3.2 and ADP v4.2. Meanwhile, the relative CF of crude oil (relative to iron) was not much higher for EPS2000 and the Recipe Endpoint, supporting our findings that showed iron with a significant contribution for those LCIA methods (Table 4, Figures 4 and 5), while the contribution of that metal in

ADP (v3.2 and v4.2) was negligible. On the other hand, according to Klinglmair *et al.* [38], Eco-indicator 99 has a lower relative CF for crude oil, similar to the Recipe Endpoint and EPS2000, but in the case study presented here, iron did not show significant contributions, and this is probably due to the specificities of the product system. The highest relative CF in AADP was from nickel [38], which confirms the reason why this metal was the main hotspot from our case study.

2.3. Recommendation of Abiotic Resource LCIA Methods

For each of one of the resource assessment levels (RAM, midpoint, endpoint), we proposed recommendations for the use of LCIA methods, based on the theoretical criteria assessment (Section 2.1), and with support from the case study (Section 2.2). As we can see in Table 1, CEENE v2.0 (CEENE with regionalized CF based on LREx) is the most suitable RAM due to the highest final score. However, we noticed that ICEC/ECEC also had a high final score; thus, since this method is operational for extended input-output LCI, we recommend it for that LCI approach; while CEENE v2.0 is recommended for process-based and hybrid LCI approaches. Further, based on Liao *et al.* [8], who recommends the SED method, and the concept introduced by ICEC/ECEC, which proposed complementary assessment for RAM, we make an additional (and optional) recommendation for using SED as complementary to the CEENE v2.0 (for the applicable LCI approaches).

For the midpoint assessment, ADP presented the higher final scores (Table 2) and thus is recommended as the midpoint LCIA method. Since it has different approaches (e.g., ultimate reserves), our recommendation is for the reserve base approach, as suggested in ILCD [3]. This is mainly due to the higher environmental relevance of that approach, *i.e.*, on one hand, the increase in resource scarcity leads to the exploitation of reserves that are less economic (e.g., marginal reserves), which are not accounted for in the economic reserve approach, and on the other hand, the ultimate reserve approach also includes reserves with a very low concentration, which may provide inconsistent results. This decision can be corroborated by the case study (Figure 4), in which the relevance of metals and minerals seemed to be negligible in the ultimate reserve approach.

For the endpoint assessment, the Recipe Endpoint and EPS2000 had the highest scores (Table 3), and are recommended as the endpoint LCIA method. Nevertheless, due to their low final score (3.5) in comparison to other LCIA methods from other approaches (CEENE v2.0 and ADP), this recommendation is made with limitations. Additionally, considering that the authors from the Recipe Endpoint, OGD and SuCo are from the same team (Radboud University and PRé Consultants), and also based on [49], we can assume that new versions of the Recipe Endpoint may include those new LCIA models. In that case, based on Tables 2 and 3 the score from the Recipe Endpoint in scientific robustness could increase. Thus, a study similar to this one should be performed again in the near future, in order to update the scores according to new versions that may come up.

2.4. Future Challenges and New Trends

The LCA scientific community has not yet reached consensus on how to evaluate resources. As previously mentioned, traditional approaches may be classified into three levels (Figure 1). However, there are new frameworks for the impact assessment of this category [6,7], showing that the LCIA methods available in literature are not yet consolidated, and new trends may appear in the future.

According to van Oers [36], resource depletion assessment at the midpoint and endpoint levels does not need to be regionalized. However, we cannot draw the same conclusion for RAM, where some type of resources may need to be assessed by spatial-differentiated CF, as done in CEENE v2.0 for land use (by LREx). Other RAM may follow the same trend, as ICEC/ECEC and SED for land use. Further, RAM may also need to regionalize other elementary flows, such as biotic resources and water. Regarding midpoint LCIA methods, we noticed an evolution, from the more traditional approach (EDIP), which assesses the availability of resources and, for the ADP, their extraction rate, for more recent methods that evaluate the decrease in the ore grade, as the Recipe Midpoint, ORI and OGD. Moreover, there are new trends that include the resources in the anthroposphere, for metals, as proposed in AADP. Currently, these new approaches are not totally suitable for LCA, due to the low number of CF, but this reality might change in the future (e.g., [42]). At the endpoint level, the assessment usually has higher uncertainties than at the midpoint level. However, newer LCIA models seem to be more scientifically robust, with fewer uncertainties (e.g., SuCo), and may be incorporated into traditional endpoint LCIA methods (e.g., Recipe Endpoint). Likewise, even though criticality does not yet have an operational LCIA method available, it is a well-established resource management methodology that may be incorporated into LCA in the future, especially when considering economic and social issues in LCSA [7,54].

Moreover, we could see that there are already a few operational LCIA methods with alternative approaches (outside of traditional LCA), for instance ICEC/ECEC, SED and Exergoecology, where concepts from Emergy and cradle-to-cradle (or grave-to-cradle) approaches, that have a high sustainability appeal, are brought into LCA.

3. Experimental Section

In order to search for different operational LCIA methods available in literature, we used different keyword combinations (e.g., resources and LCA) on web tools, such as Web of Science. Articles published from the last 20 years, until December of 2014, were considered. After that, the articles that referred to the LCIA methods *per se* were selected, *i.e.*, we excluded case studies that used those LCIA methods. Finally, we evaluated them through two criteria: (1) Scope: in which the amount of elementary flows that could be accounted for was evaluated, *i.e.*, the amount of CF available in the LCIA method. The availability of regionalized CF was also considered, but since spatial-differentiation in LCIA is not applicable to resource depletion assessment [36], this was considered solely for the RAM (not for midpoint and endpoint LCIA methods); (2) Scientific robustness: in which the model behind the LCIA method was evaluated, how it was scientifically proposed (theory used and/or cause-and-effect relation), how clear was the documentation, and if the method was fully operational. Other criteria could be used in our evaluation (e.g., acceptance by LCA community), but we preferred to focus on rather technical criteria. We gave scores between one (the lowest) and five (the highest) for each of these criteria and later we calculated an arithmetic average in order to provide a final score for each of the LCIA methods evaluated.

After the theoretical assessment of the LCIA methods, some of them were applied in a case study of ethylene production. For that, two scenarios were considered:

- A traditional FE, which was based on the data in the ecoinvent [55] dataset named "ethylene, average (RER) production, Alloc Def" (There is no dataset in ecoinvent for Brazilian ethylene). The inputs and outputs in this dataset are arranged as aggregated LCI; thus, it is not possible to clearly identify the life cycle stage of each elementary flow;
- A BE, from Brazil, where sugarcane is produced to generate ethanol, that is further dehydrated into ethylene. Therefore, Cavalett *et al.* [56] was used for sugarcane and ethanol data and the Swedish Life Cycle Center (CPM) database [57] for the ethanol-to-ethylene process unit. Sugarcane and ethanol production considered in reference [56] is from advanced technologic cultivation and production systems, from the state of São Paulo (Brazil). The ethanol-to-ethylene process unit is based on pilot scale data.

After modeling the life cycle of these two scenarios of ethylene, we performed an LCIA through different resource-based LCIA methods. Then, we evaluated which scenario had the best/worst results and searched for the main hotspots that each of these LCIA methods identified.

4. Conclusions

Through this study, we found 19 different LCIA methods for assessing the AoP Resources. We then made an assessment based on two criteria and, with support from a case study, were able to recommend the CEENE method v2.0 (with optional complementary assessment by SED) for process-based and hybrid LCI, and ICEC/ECEC for extended input-output LCI, at RAM level; ADP (reserve base) for midpoint level; and EPS2000 and the Recipe Endpoint for the endpoint level (with the possibility of only being the Recipe Endpoint in the future). In addition, it was possible to notice that the evaluation of the AoP Resources is not yet well established in the LCA community, not only due to the recent development of several new LCIA methods with different approaches, but also due to the new propositions on how this AoP should be assessed. In this sense, it is important to highlight the importance of performing a study similar to this one in the near future, as new LCIA methods and also new (and upgraded) versions of the current LCIA methods may appear.

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

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