This paper is part of the IRGC project "Ensuring the environmental sustainability of emerging technologies".
Suggested citation: Moretti, C. (2022). Ensuring the environmental sustainability of emerging technologies applications using bio-based residues. In M.-V. Florin (Ed.) (2023). *Ensuring the environmental sustainability of emerging technologies* (Edited volume). Lausanne: EPFL International Risk Governance Center.
DOI: 10.5075/epfl-irgc-298445

Ensuring the environmental sustainability of emerging technologies applications using bio-based residues

Christian Moretti[1]

Table of contents

[1] ETH Zurich, Department of Environmental Systems Science, 8092 Zurich, Switzerland, christian.moretti@usys.ethz.ch.

Introduction

The European Green Deal with related EU chemical and bioeconomy strategies aim to accelerate the development of innovative conversion technologies to produce bio-based alternatives in European sectors traditionally dominated by petrochemical products. As a result of this effort to reduce fossil fuel dependence and climate change impacts, the growing global trend of innovative bio-based commodities is expected to continue. The significant investments in future emerging technologies for bio-based products should be guided towards those that are environmentally sustainable. This is possible only with science-based evidence on their environmental impacts at an early stage.

In particular, unlocking the full potential of locally sourced bio-based residues is crucial to expanding the number of bio-based products produced sustainably in the EU. This feedstock does not generate concerns about food security and land competition. Furthermore, it is usually cheaper than dedicated crops and does not require transoceanic imports. For these reasons, products from bio-based residues are expected to be the core of future bio-based innovation to move towards a circular economy via better valorization of natural resources. Moreover, avoiding dedicated cultivation with required fertilizers, fuel consumption in tractors, irrigation, etc., bio-based residues are expected to have a lower climate change impact than dedicated crops.

Life cycle assessment (LCA) methodology is an internationally standardized method to assess products' and services' life cycle environmental impacts. Various policy regulation mechanisms already rely on LCA results to incentivize bio-based products based on their environmental performance. However, these policy instruments mostly cover climate change impacts, i.e., incentives are based on greenhouse gas mitigation potentials (Edwards et al., 2017). So, other environmental tradeoffs typically existing between bio-based and petrochemical products are neglected. When the scientific literature considered additional environmental impact categories, bio-based products often showed higher eutrophication and water depletion impacts than their petrochemical counterparts due to biomass cultivation (EC, 2019). So far, there is still a lack of comprehensive understanding of environmental tradeoffs of emerging products made from bio-based residue streams not requiring dedicated cultivation.

This paper aims to reflect on critical considerations necessary to avoid that a greenness claim of a future technology utilizing a bio-based residue is challenged at a late investment stage for its adverse environmental impacts.

1. Background

Based on the findings of recent LCA literature, the calculated environmental impacts of bio-based products from less economically valuable or physically smaller streams are expected to be more affected by the selection of a so-called multifunctionality approach than the impacts of products from dedicated crops. Bio-based residues are regularly produced from multi-output or multifunctional systems. So, conducting an LCA of a product from a bio-based residue regularly requires multifunctionality solutions (also commonly referred to as "allocation practices") to allocate a fraction of the environmental impact to the bio-based residue. Suppose an LCA expert is investigating the environmental impact of a bio-based product made from wheat straw, this expert needs to divide the environmental impact of wheat cultivation between wheat grain and straw, since only the straw is part of the life cycle of the bio-based product. Economic allocation is often used to make this distinction, reflecting the difference in price between straw and grain. Wheat cultivation exists primarily to provide grain to the market and not straw. Accordingly, taking an example from the literature, 17.7% of the total cultivation emissions of wheat are allocated to straw and 82.3% to grain (Lokesh et al., 2017).

Despite the existence of ISO LCA methodology standards (ISO, 2006b, 2006a), modelling multifunctional processes is one of the most controversial methodological aspects in the LCA literature, with low convergence in recommendations in LCA guides of different countries and sectors. For example, an LCA guide used in a certain country or sector might recommend mass allocation between wheat straw and wheat grains. Another LCA guide might recommend the subtraction of the impact caused by the production of the product replacing wheat straw from its current use. Using these methods instead of economic allocation significantly changes wheat straw's environmental impact. As a result, it is not uncommon to find the life cycle environmental impact of the same bio-based residue varying from highly positive to highly negative as a consequence of adopting different multifunctionality approaches (Hermansson et al., 2020).

The system modeling approach is one of the key methodological decisions/preferences influencing multifunctionality practices. There are two major, well-distinguished modeling approaches: attributional and consequential (Schaubroeck et al., 2022). Information regarding the definition and critical differences between these two modeling approaches can be found in Table 1. The same table also provides the definition and main features of "prospective LCA", which is another system modeling approach often mentioned in this paper. The selection of a prospective LCA modeling approach is linked to the technology under assessment and its temporal scope (Cucurachi et al., 2018)[2]. Adopting a prospective LCA modeling approach has no direct effect on multifunctionality choices. A prospective LCA can be either a prospective attributional LCA or a prospective consequential LCA, with multifunctionality approaches selected accordingly. The relevance of a prospective LCA approach in this paper originates from the fact that most conversion technologies for bio-based residues have not yet been commercialized. Prospective LCA allows one to determine the environmental impacts of these technologies at a future large-scale commercial level.

2. Aim

In discussing critical considerations necessary to avoid that a greenness claim of a future technology utilizing a bio-based residue is challenged at a late investment stage for its adverse environmental impacts, this paper considers two primary aspects. The first aspect concerns the shift of environmental burden towards another environmental impact (e.g., a product incentivized based on its low climate change impact that might cause higher toxicity exposure for the environment and humans) or sector (e.g., diverting a bio-based residue from its current application might have some counterfactual impacts). The second aspect regards the effect of adopting a different multifunctionality modeling approach for bio-based residues in the LCA of a product. This reflection provides a deep dive into challenges in evaluating and quantifying the environmental sustainability of an emerging technology which converts bio-based residues before investment and production has started. Various examples of emerging conversion technologies to convert bio-based residues into a heterogeneous range of high-value products, designed for different markets and competing for these bio-based residues are presented in this paper.

Table 1 | Definitions and critical differences in LCA system modeling approaches mentioned in this paper

Attributional	Consequential	Prospective
Attributional is a system modeling approach in which the environmental impact is attributed to a product by partitioning the system's processes via allocation methods commonly based on economic, mass or energy values. So, if the allocation method is consistently chosen in all LCAs, summing up the environmental impacts of all worldwide products in the temporal scope of the LCA leads to the total observed environmental burdens globally at that time. Attributional LCA is the most applied modeling type in EU policies and ecolabeling given that it has lower uncertainties than consequential LCA (Giuntoli et al., 2019).	Consequential is a system modeling approach which measures the environmental impact of a product through any expected changes in impact due to the production of that product. The systems modelled in consequential LCAs include all processes affected by the decision to produce such a product. The processes to include are determined based on the cause-and-effect chain initiated by the decision to produce the product. The chains may include processes outside the supply chain, or avoided environmental burdens indirectly caused by introducing the potential co-products in the market, leading to the displacement of conventional market products (UNEP/SETAC, 2011).	The LCA community uses different names and definitions to refer to prospective LCA. Among the most common alternative names are *ex-ante* LCA and early-stage LCA. A prospective LCA is a particular type of LCA investigating an emerging technology and having a future temporal scope. An LCA can be defined as prospective "when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modeled at a future, more-developed phase (e.g., large-scale production)" (Arvidsson et al., 2017). So, compared to conventional LCAs, it is important to avoid a mismatch.

[2] See also the paper written for the ESET project by Stefano Cucurachi and Carlos F. Blanco, "Practical solutions for *ex-ante* LCA illustrated by emerging PV technologies" (2022).

The following emerging products are considered based on recently published prospective LCAs:

1. **Plastics from used cooking oil** (Moretti et al., 2020)
2. **Fuels from potato peels** (Moretti et al., 2022)
3. **Fuels from biogenic carbon emissions** (Falter et al., 2020)
4. **Asphalts from lignin** (Moretti et al., 2021)

The LCAs of these products determined the environmental impact reduction compared to their conventional counterpart, i.e., petroleum-based plastics, fuels and asphalt. While investigating climate change impacts is a common practice in the LCAs of bio-based products, the four prospective LCAs used here as examples considered a broad spectrum of potential environmental impacts. This allows understanding whether typical environmental tradeoffs of products from cultivated biomass compared to their conventional (fossil) counterparts (such as higher eutrophication impacts) also apply to products from bio-based residues (not requiring dedicated agricultural activities).

The insights gained from these four LCAs (e.g., on environmental hotspots and tradeoffs of the products analyzed) are used to provide recommendations on how to produce products from bio-based residues sustainably, which would be preferable from a long-term environmental standpoint to the current situation, considering the risks of existing processes to environmental sustainability. Given the holistic overview of applications and environmental impacts considered in these four LCAs, they are used to draw general lessons and recommendations (that are potentially applicable also to other domains) for guiding investment and research toward environmentally sustainable technologies.

Furthermore, to avoid severe consequences in investment decision-making for future technologies utilizing bio-based residues, the effect of multifunctionality practices on the environmental impacts of these emerging products needs to be well understood. The four bio-based residues investigated in the selected LCAs are key examples since they reflect the entire spectrum of relevant cases from an LCA multifunctionality perspective:

1. **Residues already highly demanded by the market for high-value applications.** This is the case of used cooking oil which is used worldwide for renewable diesel (Mandolesi De Araújo et al., 2013).
2. **Residues already sold for other lower revenue uses.** For example, potato peels are sold as animal feed but could be valorized into fuels (Moretti et al., 2022).
3. **Residues currently polluting the environment.** For example, carbon emissions of biological origins released into the atmosphere could be captured and transformed into high-value products (Falter et al., 2020).
4. **Residues currently used by the potential producer (not sold).** This is the case of lignin (black liquor) which is currently burned for internal energy needs by pulp mills and lignocellulosic biorefineries (Hermansson et al., 2020).

3.

Data: Outcomes of the considered LCAs

Figure 1 shows the life cycle climate change mitigation potentials of the four products derived from the respective bio-based residues considered by this paper.

3.1 Plastics from used cooking oil

The prospective LCA of polypropylene (PP) from used cooking oil (UCO) (Moretti et al., 2020) showed a 40-62% climate change impact mitigation potential compared to petrochemical PP. This range reflects different allocation methods applied for UCO at the process level. PP from UCO also showed a much lower climate change impact than bio-based PP made from sugarcane and woody biomass (up to 80% lower). PP from UCO is a better alternative to both petrochemical and bio-based PP from dedicated crops. However, UCO is a very limited feedstock and is already largely used to produce renewable diesel. The reduction of climate change impact allowed by renewable diesel from UCO compared to oil diesel is 80-90%, which is much higher than 40-62% obtained with UCO PP replacing petrochemical PP. Thus, it is questionable if using UCO to produce more PP than renewable diesel is beneficial, especially considering that other bio-based types of diesel have a much lower climate mitigation potential (Edwards et al., 2017).

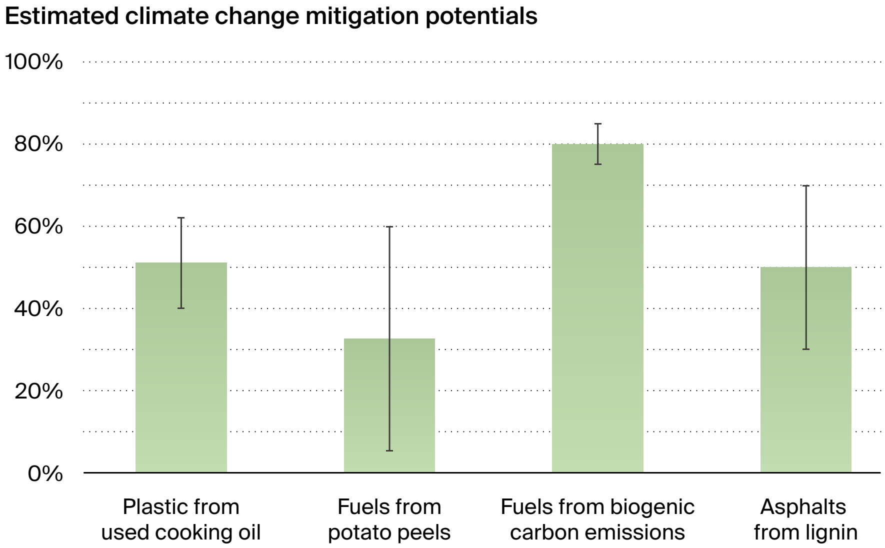

Figure 1 | Climate change mitigation potentials of the considered products expressed as a percentage compared to the conventional (fossil) counterparts taken as 100%. Error bars represent both data and methodological uncertainties. Data uncertainties include prospective uncertainties (primarily due to future energy mixes) and methodological uncertainties (primarily due to multifunctionality approaches).

Nonetheless, the LCA performed by Moretti et al. (2020) concluded that the climate change mitigation potential for PP from UCO could be further improved by recycling the embedded biogenic carbon content in durable plastic applications over different life cycles. The same LCA also concluded that the climate change impacts of both UCO-based PP and diesel could be significantly improved by using renewable electricity to power the process and produce renewable hydrogen via electrolysis. For PP from UCO, renewable gas produced as a co-product could be used to partially replace liquefied petroleum gas (LPG) consumption for steam cracking. However, renewable gas is currently sold on the market. So, there might be tradeoffs with natural gas replacements allowed by renewable gas.

The same LCA also showed that petrochemical PP from UCO has a much lower fossil fuel resource use (80-86%) than petrochemical PP. The LCA did not lead to robust conclusions due to both data and methodological uncertainties for other impact categories such as toxicity, ozone depletion, and freshwater eutrophication.

While multifunctionality uncertainty was relatively low for climate change and fossil resource depletion, it was much higher in other categories. Therefore, multifunctionality uncertainties on the environmental impacts of the final products are regularly much higher for several environmental impacts than others. For example, if UCO is no longer considered waste (free of burdens) but a by-product (given its high market value today), an allocation method is necessary. The so-called 50/50 allocation method applied to UCO open-loop recycling would increase the environmental impacts of UCO-based PP between 25% and 160% (on a weighted basis), depending on the impact category and type of primary vegetable oil, with higher variations observed for particulate matter, human toxicity, ecotoxicity, eutrophication, land use, and depletion of non-fossil resources (minerals and metals). This example also shows the complexity of analyzing an LCA outcome in cases when more than one option is possible for a key modeling parameter, such as allocation for bio-based residues. In the case of circular processes like the recovery of a residue (or waste), a deeper interpretation of LCA results becomes necessary due to the inconsistency of current multifunctionality practices and and how sensitive the outcomes are to the practice chosen.

3.2 Fuels from potato peels

The prospective LCA of jet fuel from potato peels applied both attributional and consequential approaches. According to the attributional LCA, the fuel could achieve a 60% lower climate change impact than conventional jet fuel (hence, it could be catalogued as sustainable aviation fuel and be incentivized). The high climate mitigation potential of this jet fuel assessed via attributional LCA is favored by the fact that the environmental impact of the potato by-product is only a minor fraction of the impact of the potato food processing industry. Since potato peels are a minor fraction of the economic revenues of this industry, a minor impact is allocated to them. This would not be valid if mass allocation was applied instead of economic allocation. In fact, mass (or energy) allocation would allocate impacts of similar magnitude to the potato peels and the potato food products, neglecting the fact that the potato processing industry works to generate revenues by producing food products and not energy or animal feed products. Therefore, mass allocation does not respect the allocation causality principle that should be followed according to the ISO standards at the base of LCA practice. However, for practicality, various LCA guides generally prefer allocation based on mass or energy over economic values.

The consequential LCA showed that this fuel could achieve a maximum of 40% climate change impact reduction (too low to be considered for EU incentives). Adopting consequential modelling, the impact of the potato by-products corresponds to the animal feed needed to replace the potato by-products diverted from their current use. This fact is the main reason for the lower performance assessed via the consequential LCA than via attributional LCA. In an extreme case, if imported soybean meals (with associated land-use changes) are used to replace potato peels, the climate change impact of the bio-jet fuel could become higher than kerosene. With respect to other environmental impacts, opposite outcomes between the attributional and consequential LCAs were obtained for photochemical ozone formation. Conversely, both LCAs concluded that the investigated fuel causes lower fossil fuel depletion but higher terrestrial eutrophication and acidification than kerosene. Since worldwide policy incentives could be based on LCA tools following either one or the other approach (or a mix of the two), the same fuel could be considered sustainable and receive an incentive following the method applied in one country but not in another country.

Since the system analyzed in attributional LCAs is only made of processes directly linked to the product's supply chain, displacement effects on the animal feed or markets are not captured using this type of modeling. Thus, applying a consequential LCA when the plan is to divert a bio-based residue from another market is highly recommended to avoid issues at a later investment stage. In this way, it is possible to change a technology design in time (e.g., targeting the design to convert a different bio-based residue) to avoid potential adverse environmental and economic impacts in the long term.

However, capturing counterfactual aspects makes the consequential LCA more uncertain. This is even more valid for prospective LCAs. In fact, since this fuel technology has a low technological readiness and will take years before being marketed, forecasts of future markets are more uncertain than current marginal markets. This also applies to the substitution of the fuel's co-products. Therefore, given this additional complexity in consequential LCAs, the case of conflicting prospective consequential LCAs will not be rare. Despite these challenges, a prospective consequential LCA is the most powerful tool to detect counterfactual burden-shifting of environmental issues due to the utilization of a constrained resource.

3.3 Fuels from biogenic carbon emissions

A recent prospective LCA of innovative jet fuel from biogenic carbon emissions estimated a climate change mitigation potential of about 80% (Falter et al., 2020). The captured biogenic carbon emissions are converted into jet fuel via a solar thermochemical fuel pathway. To achieve such a high mitigation potential, solar energy produced in a location with high direct normal irradiance is a key choice.

It is fair to acknowledge that this LCA mostly investigated the production of fuel from carbon emissions captured via direct air capture. The solar thermochemical fuel production from a biogenic carbon emission point source is only discussed as a sensitivity analysis in this LCA. Besides generating low climate change impacts and fossil resource depletion, the LCA of fuels from biogenic carbon emissions showed high particulate matter formation, terrestrial acidification, freshwater consumption and human toxicity impacts. The main source of these impacts is found in the chemical process of capturing carbon dioxide (CO_2).

Fuels from biogenic carbon emissions are a key technology for carbon neutrality. However, the high climate change mitigation potential for this type of fuel relies on the methodological assumption that those carbon emissions would be emitted if this fuel is not produced. An allocation by physical causality or consequential modeling is necessary to account for this fact. As it was recently well illustrated in a scientific article on this specific matter (Müller, Kätelhön, Bringezu, et al., 2020), simple allocation methods based on mass or economic shares cannot properly account for avoiding these emissions or any other waste of concern. They would lead to a completely different outcome penalizing this type of fuel.

Driven by this need to increase the comparability of outcomes of LCAs of CO_2-based products, a recent guideline has been internationally developed (Müller, Kätelhön, Bachmann, et al., 2020). However, the recommendations of this guideline are far from being broadly known and implemented at an international policy level. Furthermore, it must be kept in mind that the recommended method (physical causality allocation or consequential approach) does not distinguish between CO_2 sources. Based on this method, fossil CO_2 sources whose use leads to waste streams with high CO_2 concentrations, which are easier to separate and capture, are environmentally favored over biogenic CO_2 sources whose use results in lower CO_2 concentrations or direct air capture technologies. So, for the same energy source, investing in capturing and utilizing biogenic CO_2 sources or capturing CO_2 directly from the air is penalized by this approach. This would not be true utilizing a different approach distinguishing between fossil and biogenic sources.

3.4 Asphalts from lignin

The prospective LCA of bio-based asphalts using lignin to replace bitumen estimated a climate change impact reduction of 30–75% compared to conventional asphalt. Hence, storing the high biogenic carbon content of lignin in asphalts has a high potential to mitigate the climate change impact of asphalts. With lignin extraction in pulp mills, there would be the need to use natural gas and hog fuel (low-value biomass) to replace the black liquor no longer available for steam production. Besides the fuel for heating the steam source to replace the no longer available fraction of black liquor from which lignin is extracted, the percentage of lignin replacing bitumen is a key factor influencing the environmental performance of bio-based asphalts. Therefore, lignin-based asphalt needs to be carefully designed from this point of view. This LCA shows low environmental gains in replacing other components of the asphalts that are not bitumen with lignin. Hence, filling asphalts with lignin is not enough if a high percentage of bitumen is not replaced.

The production of lignin (excluding biogenic carbon intake) was one of the main sources of environmental impacts of lignin-based asphalts. Lignin with low climate change impact can be obtained using hog fuel to replace the black liquor. Conversely, using natural gas to replace the black liquor leads to a much higher climate change impact for the same lignin and lower climate change mitigation benefits for lignin-based asphalt. Besides steam production, the other main sources of the environmental impact of lignin production are the production of sulfuric acid and liquid CO_2.

The high climate change mitigation potential of lignin-based asphalts was also favored by using economic allocation at the level of the pulp mill since lignin has a lower market value than pulp. Applying mass allocation instead of economic allocation would have led to a much higher impact for the same lignin. This also applies to bitumen which is a residue of oil refining. Hence, the cradle-to-gate comparison between lignin-based and conventional asphalts is meaningful only if the same allocation principle is applied to both lignin and bitumen. However, guides for environmental footprint declarations in the construction sector often have a predefined value for bitumen's environmental impact, which is based on one or the other principle.

Furthermore, in the LCA, the physical biogenic content of lignin (which is high) was considered and preferred to an allocated biogenic carbon value which would have been lower. However, various LCA guides suggest allocating the biogenic carbon as any other process input, which would penalize this type of product compared to others.

4.

Lessons learned and recommendations for emerging technologies utilizing bio-based residues

The considered prospective LCAs were used to show that the life cycle climate change impacts of emerging products from bio-based residues are usually lower than their fossil counterparts. For example, climate change impact reductions of 30—70% can be achieved by replacing current asphalts with lignin-based asphalts and 40—62% by replacing petrochemical PP with PP from used cooking oil. However, the following considerations apply:

1. High climate change mitigation performances achieved by specific conversion technologies and bio-based residues cannot be generalized since environmental optimization of various factors plays a crucial role in achieving a positive environmental performance. Using renewable energy and green chemicals is key to achieving high climate change impact reduction. Low-value biomass or biogas are key choices for products from bio-based residues, although they might be more expensive than liquefied petroleum gas or natural gas. Using fossil energy in the production process of products from bio-based residues could lead to higher climate change impacts than their petrochemical counterparts used today. Suppose the pulp mill or biorefinery chooses natural gas to replace lignin as internal fuel, this could result in a higher environmental impact for bio-based asphalts than conventional asphalts. Besides green energy and fuels, the supply chain, production process, and composition (e.g., some products are only partly bio-based) are key aspects to be analyzed.

2. Positive performances in terms of climate change impacts are usually accompanied by savings of a similar magnitude for the impact category regarding depletion of fossil fuels. However, tradeoffs with conventional products from fossil resources regularly occur in some other impact categories. This fact has widely been observed for products from dedicated crops and is confirmed to apply also to products from bio-based residues. For example, significantly higher acidification and terrestrial eutrophication impacts than fossil products can also be expected for products from bio-based residues. Counterintuitively, this does not apply only to products made from dedicated crops. The allocation to bio-based residues of even a small percentage of agricultural activities such as fertilizer volatilization and combustion of fuels in tractors easily leads to higher eutrophication and acidification impacts since petrochemical products require no fertilizers or tractors. Furthermore, the conversion of bio-based residues into high-value products requires pre-treatment with chemicals (e.g., sulphuric acid), often leading to high toxicity-related human and environmental impacts, especially in the case of low conversion yield.

3. Bio-based residues are scarce, and many technologies compete for the same bio-based residue. Therefore, the decision-makers must be careful when diverting bio-based residues from other uses, especially in the case of low-yield technologies. Consequential LCAs are designed to understand this aspect and might lead to significantly different outcomes than attributional LCAs for the same bio-based residue. This is often the case if it is diverted for another application (e.g., animal feed), causing high indirect environmental impacts. Attributional LCAs cannot spot these potential burden shifts if the current use of the residue is not part of the producer's supply chain of the bio-based product. Therefore, the decision-makers should monitor with attention the effect on the current uses and the alternative chosen to replace them. However, this might be outside the supply chain and, therefore, not influenceable by the future producer of that bio-based product. Consequently, for maximized satisfaction of human and eco-systemic needs, it is necessary to involve a wide range of stakeholders (even beyond market actors) to understand which bio-based residues are appropriate for certain end uses.

4. For producers of durable applications such as bio-based asphalt, it is important to know that certain LCA methods recommended at the national or international level may not give any credits for permanent (and temporary) carbon storage. This could significantly penalize the environmental performance calculated for this type of bio-based product.

5. The environmental impact of bio-based residues is usually not trivial in the LCA of the derived products and is highly linked to the adopted allocation method. In fact, a small change in the allocation share of the main product can significantly change the allocation share of the by-product. For example, suppose the impact allocated to the main product is 90% with one assumption and a different assumption would lead to 85%. The allocation share of the by-product would increase by 50%, while the impact of the main product varies only by 5.5%.

6. Applying an allocation based on a physical parameter (e.g., a simple mass-based or energy-based allocation) to the bio-based residue often leads to a much higher environmental impact for the bio-based residue than economic allocation. In principle, these two allocation methods applied to bio-based residues often do not reflect causality as recommended by the ISO standard on top of which LCA practice is built. However, various international LCA methods and EU policies linked to alternative fuels recommend these methods over economic allocation with the goal of increasing simplicity of analysis. Therefore, producers of products from bio-based residues could be penalized in sectors or countries adopting these LCA methods. Furthermore, allocation based on a physical parameter is not suitable for mitigating undesirable use of scarce bio-based residues driven by financial return optimization instead of optimized environmental impact. If bio-based residues are increasingly demanded on the market, their price will adjust. A higher price for a bio-based residue leads to higher environmental impacts if allocated via economic value. This avoids incentivizing less efficient production of the primary product, i.e., optimizing for more "waste" production with unforeseen consequences and lower sustainability benefits in using waste feedstocks.

5. General reflections and recommendations for future emerging technologies

In terms of observations or lessons that could be transferred to other emerging technologies, for the purpose of helping decision-makers better anticipate potential adverse impacts on environmental sustainability, the following aspects are noted:

1. Generalizations and conclusions are difficult to make and can be misleading if the outcomes of a single LCA (or a set of LCAs for a single product) are transposed into another setting (e.g., different country and, therefore, different energy mix).

2. Decision-makers generally face several tradeoffs at various levels. Products with lower climate change impacts than their alternatives might show other environmental tradeoffs, e.g., higher eutrophication or ecotoxicity impacts. These tradeoffs should be evaluated case by case and minimized as much as possible by changing the design choices in time.

3. Optimization and decisions may not be replicable. Key decisions are often taken based on pilot plants. However, pilot plants might significantly differ from future commercialized technologies. Potential process design changes and size scaling effects depend on optimizing process synergies and future technological learning. These aspects also depend on external factors such as future infrastructural changes (e.g., in the energy mix, supply chains, etc.) In this case, prospective LCA modeling is a key tool.

4. Objectives regarding environmental impacts and economic outcomes may not align. Environmentally sustainable products generally have a higher production cost than conventional products relying on (often) cheaper fossil resources for their production. So, using natural-gas energy or certain petrochemical ingredients instead of greener alternatives in the production process of a future alternative product might be tempting. However, this could result in higher environmental impacts than the conventional products intended to be replaced.

5. Certain feedstocks or materials for future products have limited availability and their best use should be preferred. Attention is needed when diverting a scarce resource from another use which might be more environmentally attractive. A consequential LCA is the most appropriate tool to detect counterfactual impacts on the environment in these cases. However, evaluating the best use for constrained resources requires a full understanding of the context of supply chain systems and competing markets, which may not exist until a market is created.

6. Uncertainty in future incentives due to inconsistency in multifunctionality practices adopted worldwide to certify the environmental sustainability of future products can have severe consequences in making investment decisions about certain products. In this sense, ISO LCA standards have failed in their role to "standardize" (Schaubroeck et al., 2022; Weidema, 2014). So far, the consequences of this fact have been investigated only incidentally when dealing with the climate change impact of a specific product, and it is rare to take a holistic perspective on multiple products intended for different uses and sectors and at the same time on multiple environmental impact categories. Therefore, there is an urgency to provide clear and internationally acknowledged guidance to avoid generating arbitrary or extreme results with consequent erroneous recommendations to the study's commissioner. This applies especially to products from residual streams, residues, and wastes or emissions, which are at the base of a future circular economy.

Acknowledgements

IRGC would like to thank Iris Vural-Gursel for offering comments on a first draft of this paper. The views presented in this article are those of the author and are not a consensus judgement by IRGC.

References

Arvidsson, R., Tillman, A. M., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2017). Environmental assessment of emerging technologies: Recommendations for prospective LCA. *Journal of Industrial Ecology*. doi.org/10.1111/jiec.12690

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of emerging technologies. *Procedia CIRP, 69*, 463–468. doi.org/10.1016/j.procir.2017.11.005

Edwards, R., Padella, M., Giuntoli, J., Koeble, R., O'Connell, A., Bulgheroni, C., & Marelli, L. (2017). *Definition of input data to assess GHG default emissions from biofuels in EU legislation, Version 1c*. doi.org/10.2790/658143

EC. (2019). *Environmental impact assessments of innovative bio-based product. Task 1 of "Study on support to R&I policy in the area of bio-based products and services " – Study*. doi.org/10.2777/83590

Falter, C., Valente, A., Habersetzer, A., Iribarren, D., & Dufour, J. (2020). An integrated techno-economic, environmental and social assessment of the solar thermochemical fuel pathway. *Sustainable Energy and Fuels, 4*(8), 3992–4002. doi.org/10.1039/d0se00179a

Giuntoli, J., Bulgheroni, C., Marelli, L., & Sala, S. (2019). *Brief on the use of Life Cycle Assessment (LCA) to evaluate environmental impacts of the bioeconomy. May*.

Hermansson, F., Janssen, M., & Svanström, M. (2020). Allocation in life cycle assessment of lignin. *International Journal of Life Cycle Assessment*. doi.org/10.1007/s11367-020-01770-4

ISO. (2006a). *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines*. www.iso.org/standard/38498.html

ISO. (2006b). *ISO14040:2006 Environmental management – Life cycle assessment – Principles and framework*. www.iso.org/standard/37456.html

Lokesh, K., West, C., Kuylenstierna, J., Fan, J., Budarin, V., Priecel, P., Lopez-Sanchez, J. A., & Clark, J. (2017). Environmental impact assessment of wheat straw based alkyl polyglucosides produced using novel chemical approaches. *Green Chemistry, 19*(18), 4380–4395. doi.org/10.1039/c7gc01719g

Mandolesi De Araújo, C. D., De Andrade, C. C., De Souza E Silva, E., & Dupas, F. A. (2013). Biodiesel production from used cooking oil: A review. *Renewable and Sustainable Energy Reviews, 27*, 445–452. doi.org/10.1016/j.rser.2013.06.014

Moretti, C., Corona, B., Hoefnagels, R., van Veen, M., Vural-Gürsel, I., Strating, T., Gosselink, R., & Junginger, M. (2021). Kraft lignin as a bio-based ingredient for Dutch asphalts: An attributional LCA. *Science of the Total Environment*. doi.org/10.1016/j.scitotenv.2021.150316

Moretti, C., Junginger, M., & Shen, L. (2020). Environmental life cycle assessment of polypropylene made from used cooking oil. *Resources, Conservation & Recycling, 157* (Sept. 2019), 104750. doi.org/10.1016/j.resconrec.2020.104750

Moretti, C., Vera, I., Junginger, M., López-Contreras, A., & Shen, L. (2022). Attributional and consequential LCAs of a novel bio-jet fuel from Dutch potato by-products. *Science of the Total Environment, 813*. doi.org/10.1016/j.scitotenv.2021.152505

Müller, L. J., Kätelhön, A., Bachmann, M., Zimmermann, A., Sternberg, A., & Bardow, A. (2020). A guideline for life cycle assessment of carbon capture and utilization. *Frontiers in Energy Research, 8*. doi.org/10.3389/fenrg.2020.00015

Müller, L. J., Kätelhön, A., Bringezu, S., McCoy, S., Suh, S., Edwards, R., Sick, V., Kaiser, S., Cuéllar-Franca, R., El Khamlichi, A., Lee, J. H., Von Der Assen, N., & Bardow, A. (2020). The carbon footprint of the carbon feedstock CO_2. *Energy and Environmental Science, 13*(9), 2979–2992. doi.org/10.1039/d0ee01530j

Schaubroeck, T., Schrijvers, D., Schaubroeck, S., Moretti, C., Zamagni, A., Pelletier, N., Huppes, G., & Brandão, M. (2022). Definition of product system and solving multifunctionality in ISO 14040-14044: Inconsistencies and proposed amendments – Towards a more open & general LCA framework. *Frontiers in Sustainability*. www.frontiersin.org/articles/10.3389/frsus.2022.778100/full

UNEP/SETAC. (2011). *Global guidance principles fo life cycle assesment: A basis for greener processes and products*.

Weidema, B. (2014). Has ISO 14040/44 Failed Its Role as a Standard for Life Cycle Assessment? *Journal of Industrial Ecology, 18*(3), 324–326. doi.org/10.1111/jiec.12139