Perspective

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OSiD: opening the conceptual design of biobased processes to a context-sensitive sustainability analysis

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Abstract: Biobased production has been promoted as an alternative to fossil-based production to mitigate climate change. However, emerging concerns over the sustainability of biobased products have shown that tensions can emerge between different objectives and concerns, like emission reduction targets and food security, and that these are dependent on local contexts. Here we present the Open Sustainability-in-Design (OSiD) framework, the aim of which is to integrate a context-sensitive sustainability analysis in the conceptual design of biobased processes. The framework is illustrated, taking as an example the production of sustainable aviation fuel in southeast Brazil. The OSiD framework is a novel concept that brings the perspectives of stakeholders and considerations of the regional context to an *ex ante* sustainability analysis of biobased production. This work also illustrates a way to integrate methods from different scientific disciplines supporting the analysis of sustainability and the identification of tensions between different sustainability aspects. Making these tensions explicit early in the development of biobased production can make them more responsive to emerging sustainability concerns. Considering the global pressure to reduce carbon emissions, situating sustainability analyses in their socio-technical contexts as presented here can help to explain and improve the impacts of biobased production in the transition away from fossil resources. © 2021 The Authors. *Biofuels, Bioproducts and Biorefining* published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Key words: sustainable process design; sustainability analysis; stakeholder engagement; aviation biofuel; responsible innovation; biorefineries

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Introduction

Biobased production has been promoted as an alternative to fossil-based production to mitigate climate change.[1] However, concerns about the impacts of biobased production on sustainability have put its desirability into question.[2,3] Concerns over the sustainability of biobased products include food security impacts related to the use of food crops, land use changes in feedstock producing regions, and negative impacts on the livelihood of local communities.[4–6] These examples indicate that tensions can emerge between sustainability objectives and concerns, and that these depend on the sociotechnical context around biobased production.

Conceptual process design, as part of research and development (R&D), is used to explore and evaluate potential applications of emerging technologies and their configuration, to decide where to dedicate further research.[7,8] For example, it is common that conceptual processes are designed to assess, select and / or optimize biomass conversion alternatives to obtain a target biobased product. In this way, conceptual design exercises can have an impact on the direction of a biobased innovation as it goes from conceptual to more detailed designs and implementation. In its scope, conceptual process design has been mostly focused on economic feasibility, and more recently on sustainability too - although the focus has been mostly limited to climate change and efficiency metrics.[9] Opening conceptual design or broadening its scope to considerations of the sociotechnical context and the perspectives of stakeholders around biobased production can therefore serve to identify and respond to sustainability concerns and tensions early in their development.

In this work we present the Open Sustainability-in-Design (OSiD) framework, which aims to integrate a context-sensitive sustainability analysis in the conceptual design of biobased processes. This work derives from reflection over a previous project on the production of biobased sustainable aviation fuel (bio-SAF) in southeast Brazil, which we use to illustrate the framework. While we refer to relevant tasks and results obtained within this project, the focus here is on the overall framework as a novel perspective for the early stage design of biobased processes. These results are described in more detail in separate publications focused on the techno-economic, environmental and societal studies that were part of the project.[10–18]

In particular, the OSiD framework allows (1) an integration of the perspectives of stakeholders and considerations of the regional context to an *ex ante* sustainability analysis of biobased production alternatives, (2) combination of methods from different scientific disciplines to support the analysis of sustainability in a conceptual process design project, (3) identification of sustainability tensions with regard to the project background (related to, e.g., objectives and technologies in consideration) and the local context that can include, for instance, certain sustainability objectives or stakeholder priorities. Making these tensions explicit early in the development of biofuels can contribute to making biofuel innovations more responsive to emerging sustainability concerns. This achievement would be significant for biofuels, specifically, considering the ongoing sustainability controversies about them. Overall, considering the global pressure to reduce carbon emissions, situating sustainability analyses in their socio-technical contexts can help understand and improve the impacts of biofuels in support of a sustainable transition away from fossil fuel resources.

Open sustainability and open design of biobased processes

Sustainability is a concept open to interpretative flexibility where different people may consider something sustainable or not depending on their own perspectives and values.[19] When stakeholders from different backgrounds and with different perspectives need to work together, as in the case of biobased production, it is likely that they will have a different vision on how a sustainable biobased production should be in practice. Not having an explicit understanding on what is desirable leaves space for ambiguity and can contribute to the emergence of differences between stakeholders. The case described by Asveld and Stemerding illustrates this: A cleaning product company aimed to develop a sustainable biobased product with lower environmental impacts than alternatives in the market, as measured by a Life Cycle Assessment (LCA).[2] However, they received unexpected criticism from a societal group that put the sustainability of the product into question based on socio-economic and environmental risk beyond what is measured in a typical LCA, and this ultimately led to the abandonment of the innovation.[2] In this case, there was ambiguity around what the different actors considered a sustainable product. This example points to a need for a sustainability understanding that is open to the perspectives and values of stakeholders related to biobased production.

Although efforts have been made to develop methodologies for the design of sustainable biobased processes, they are often challenged by disciplinary boundaries that yield a narrow scope of analysis, making them closed to considerations of contextual settings and stakeholder perspectives.[9] The case just mentioned above illustrates this challenge. This means that, during the design of biobased processes, there has been a limited consideration of societal concerns, tensions, and diverging visions of sustainability that emerge with this production approach.

Opening R&D to the perspectives and participation of stakeholders has been approached in academic research and science policy through responsible research and innovation (RRI) and open science. These approaches seek to align scientific and technological developments with societal values for a more sustainable society.[20] For this, some authors have suggested existing tools and methods from academic fields in the humanities and social sciences.[21–23] For example, stakeholder mapping and diverse engagement strategies can be used to open a dialogue and bring about an inclusive understanding and development of a technology.[24] Value-sensitive design (VSD), which is an approach to the integration of stakeholder values (e.g., care for nature and privacy) in the design of a product, has been suggested to address moral ambiguities and respond to societal concerns related to technological innovations.[25] The use of scenarios and other futuring methods has also been suggested as an anticipatory glance at the impacts and benefits of a technology, and to also understand the complex configuration that their development may involve (regarding actors' expectations, regulations, etc.).[26,27] Even more, van de Poel *et al.* propose a conceptual model to integrate RRI in industrial practice, suggesting methods like those above for operational corporate activities.[22] However, despite the broad discussion about opening research and innovation to stakeholder participation, in industrial practice its application has been limited,[28] with some authors observing that academic RRI developments are not in line with common industrial practice.[29]

There is an opportunity during conceptual process design to bring forth openness and responsible innovation practices at the early stages of a biobased innovation. That is, as conceptual design is used to explore the potential of a technological innovation and assess its feasibility before large investments are put into place,[8] this exploration can be extended to consider stakeholder perspectives or engage them in the process, and address emerging concerns and tensions when taking decisions about the direction of the innovation. In this way, the development of the technology can be responsive to societal and sustainability concerns as they emerge.

Open Sustainability-in-Design framework

The following framework aims to integrate a context-sensitive sustainability analysis into the design of biobased processes. The typical structure of the design process (i.e., problem definition, synthesis of alternatives, and evaluation) is taken as a basis for the framework. However, instead of focusing on ranking or selecting a best alternative, as is typically done in process design, with this framework the potential process alternatives are contrasted, and tensions and opportunities for future work are identified to support an open deliberation and decision making. For this, the definition of sustainability is open to stakeholders' concerns and values with regard to sustainable production, while knowledge of the local context is used to situate the evaluation of design alternatives and support future decision making. As the main focus here is on sustainability, more focus will be given to the steps pertaining to the definition and analysis of sustainability.

Defining the project

Biobased processes require the coordinated action of diverse stakeholders to support the development of a production chain from biomass production to final product because there is no single actor that possesses all the capacity, in terms of knowledge and resources, to advance a specific biorefinery.[30] Thus, in coordination with the stakeholders involved in the project, the objectives and constraints to the project are defined. This definition provides enough information to delimit the space for designing, making explicit the design aim, i.e., the production of a target biobased product(s), the processing of a specific feedstock(s) or the exploration of potential applications for a specific technology. The target production scale is defined at this stage too, as a target or as a variable. The location of biomass production and conversion should be defined as it is the basis for understanding the context of the project, setting production possibilities for the project as well as the desirable aspects the bioprocess should comply with, and which will define how its performance will be evaluated.

Besides the project partners, other stakeholders who can be affected by the development of the project are identified at this point. Stakeholders can include biomass producers, biobased product users (industrial intermediaries as well as final users), government bodies involved in the development of infrastructure, research institutes related to the development of technologies, processes and products, as well as public actors and civil society around the production chain.[31] Clearly, during the early stages of development, few aspects of a biorefinery are defined and this may limit the capacity for involving and even identifying specific stakeholders. In this case, a generic biobased production chain can be used as a proxy to start the identification of local stakeholders, who, in turn, can help with the identification of other relevant stakeholders, as shown elsewhere in the literature.[16]

Case study

The aim of the project was to identify promising production chains for bio-SAF from locally available biomass resources. The project was set in the southeastern region of Brazil, the biggest agricultural region in the country,[32] with large airports servicing major urban and industrial areas (i.e., Guarulhos and Galeao airports in Sao Paulo and Rio de Janeiro respectively). The scale of this project was not defined at the beginning of the project but it became a variable to define, taking into account: (1) the demand in the regional airports, and (2) the potential for bio-SAF production and use. The latter is related to existing or expected blending mandates and limits to their use in commercial aviation.[33] Identified stakeholders in the project were actors directly involved in the production chain, such as producers of crops suitable for bio-SAF production (e.g., sugarcane, soybean), farmer associations in the region, technology developers and companies active in, e.g., biomass conversion and crop development, airport operators, fuel distributors, and airlines operating in Brazil. Other stakeholders included certification laboratories, financing institutions, governmental bodies related to agriculture, energy and technology, as well as producers of other fuels, notably bioethanol for road transportation.

Exploring the design space

This stage is about exploring the space for designing, identifying the production potential from available resources in the target region, and sustainability aspects relevant to the development of the project and how to evaluate them.

Production

Promising feedstock and products are identified from a high-level analysis of the production potential in the region. Where biomass feedstocks are defined, the analysis is focused on the selection of a main product or product portfolio; when the project has a target product the focus of analysis becomes the biomass type and the identification of potential by-products. When having a biomass focus, a list of feedstocks available in the region is necessary, which can include sugar and oil crops, as well as residues available from agricultural and industrial processing in the same region. When the product definition is the focus, the list is focused on product types that can feed into the industrial environment in the region, or that can be connected to a supply network in demand. For this analysis, access to statistical data about industrial and agricultural production in the region is therefore advantageous.

Once available resources or target products are defined, reported or expected conversion yields can be used to derive the production and economic potential (i.e., amount of main product per year based on feedstock availabilities, and the difference between sale revenues from all products and cost from main raw materials respectively) of possible biomass and product combinations. These calculations are based on conversion yields for the main product and relevant by-products from available processing technologies. Given the high-level analysis and uncertainty of this exploration, only biomass-product combinations with significantly lower economic potential or with production potential far from the target production scale (if defined) are discarded after taking into consideration uncertainties in the calculations.

Case study

Identified feedstocks in the region included eucalyptus, macauba, soybean, and sugarcane, amongst others, and the lignocellulosic residues derived from their processing. The processing of these feedstocks for obtaining bio-SAF was explored under different conversion routes. This analysis was based on reported conversion yields as described by Alves *et al.*[10]; with the detailed specification of the conversion process and the supply chain out of scope at this point. Potential by-products under consideration included secondary fuel products derived from the process (such as naphtha and diesel) as well as higher value biochemicals. Based on economic potential results[10] the range of feedstocks was narrowed to eucalypt, macauba, and sugarcane, with succinic acid as a higher value product.

Open sustainability

Sustainability is defined through the identification of issues relevant to the project and indicators to measure these issues. The identification of sustainability issues is based on stakeholder engagements. Interviews, surveys, and other elicitation methods can be used for this purpose.[16] Indicators for evaluating these issues are selected considering the availability of data and measurement feasibility within the project, reliability and associated uncertainty, and relevance (i.e., limited to the aspects that are relevant to the design alternatives). Existing lists of sustainability issues and indicators from state-of-the-art sustainability literature can be used as starting point to define sustainability as relevant in this case study, examples include the UN Sustainable Development Goals and the related Indicator Framework,[34] as well as the multiple sustainability certification schemes and indicators sets that have been developed for biobased production (e.g., Bonsucro,[35] the Roundtable on Sustainable Biomaterials,[36] and indicator sets by Efroymson *et al.*[37–39]). However, the development of the project should remain open to the identification of aspects that do not appear in these lists, or to specify them according to the local context of the project. This openness with regards to the analysis of sustainability is necessary considering that different issues might be of more relevance in some regions or for some projects than for others. Also, some sustainability issues might be interpreted or perceived differently by stakeholders who may have different interests and priorities based on the values of the group they represent, as illustrated by the case of the national interpretation of the Roundtable on Sustainable Palm Oil.[40] Therefore, specifying sustainability with considerations of the local context is necessary for selecting and interpreting indicators. Furtheremore, local variables, such as soil condition and climate, should be taken into account when measuring environmental impacts.[38] If possible, in the project context, it is also recommended to validate the identification of sustainability issues and the selection of indicators through the participation of stakeholders.[15,41]

Case study

Based on interviews with stakeholders related to the potential production of bio-SAF, a survey with experts on biofuel production, and a sustainability literature review, sustainability issues relevant to the case study and indicators and methods for their evaluation were defined (see Table 1).[15,16] Considering data availability and capacity for evaluation, it was decided to evaluate four sustainability issues through quantitative indicators (i.e., climate change, efficiency, profitability, social development), and four qualitatively (i.e., commercial acceptability, energy security, investment security, and soil sustainability). Sustainability issues mostly related to the implementation of production and beyond the scope of design choices were left out of the selection of indicators and methods (including cultural diversity, equity, and social cohesion, and labor rights, amongst others). Below we present an overview of the four qualitative indicators only; the methods for evaluating profitability, climate change, efficiency and social development impacts are described in detail in the references indicated in (Table 1).

Commercial acceptability was explored in terms of the approval status or certification by ASTM International, in alignment with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels.[52] Certification is intended to assure stakeholders in the aviation industry that the fuel has the same safety and performance, and can use the same infrastructure, as conventional kerosene.[53] Energy security was explored in terms of contribution to energy reliability and self-sufficiency considering the concerns of government and biofuel stakeholders about these aspects, and who referred to recent

Table 1. Sustainability framework for the ex-ante analysis of bio-SAF production in southeast Brazil.

Sustainability aspects		Description	Indicator(s)	Main references
Qualitative	Commercial acceptability	Analyzed in relation to ensuring safety and a good performance of aviation biofuel	ASTM approval	16,33,42
	Energy security	Related to energy supply reliability and self-sufficiency	Potential for power generation and NREU	13,14,16
	Investment security	Related to the readiness level of new crops and technologies, and previous experience with potential crops	FRL and crop development status	16,43,44
	Soil sustainability	Regarding the protection and recovery of the soil in relation to biomass production.	Residue harvest	11,45–51
Quantitative	Climate change	Analyzed as the GHG emissions derived from the biomass production and distribution stages, and the aviation biofuel production process	GHG emissions	12–14
	Efficiency	Primarily evaluated in terms of non-renewable energy use and other mass and energy efficiency indicators related to the process	NREU	13,14
	Profitability	Analyzed in terms of the minimum selling price of aviation biofuel required to payback production expenses, including capital and operational expenses	MSP	13,14
	Social development	Analyzed in relation to impacts on national employment, gross domestic product and trade balance	Direct and indirect jobs, GDP contributions and trade balance	17

ASTM: American Society for Testing and Materials; FRL: Fuel readiness level; GDP: Gross domestic product; GHG: Greenhouse gases; MSP: Minimum selling price; NREU: Non-renewable energy use.

energy supply problems in Brazil.[16] To analyze energy security, energy use derived from the estimations in the literature[13,14] was used as a relative indication of the performance of conversion technologies on this aspect (i.e., a negative score for the alternative with highest non-renewable energy use (NREU) and a positive score for the alternative with lowest NREU). The potential of the different alternatives for power generation, which is expected to contribute to energy reliability[16], was taken as indicator of energy security for each feedstock. Investment security was explored through the readiness level assigned to conversion technologies and feedstocks. This aspect was considered according to the responses of stakeholders from the government, technology companies, and research institutes, and referencing farmers, who perceived risk in unproven technologies (including feedstocks), especially those for which they had no relatable experience.[16] For technology alternatives the Fuel Readiness Level scale was used as a reference,[43] while for feedstocks the Feedstock Readiness Level scale from the Commercial Aviation Alternative Fuels Initiative was used as a benchmark.[54] Soil sustainability was considered based on stakeholders' concerns regarding the protection and recovery of natural resources, especially with regard to deforestation and land degradation.[16] Most interviewed stakeholders showed concern about this aspect, including respondents from the government, aviation and technology companies, and research institutes.[16] Soil sustainability was studied through a review of the literature.

Design of process alternatives

Taking the process and product combinations defined in the previous steps, process alternatives are synthetized considering suitable conversion technologies, upstream and downstream processing, and mass and energy integration as in typical process design methods. If they are in the scope of the project, supply chain elements, such as biomass transportation and storage, and fuel distribution, are to be taken into account at this point. As the scope of this step is common to the engineering domain, the reader is referred to process design and other engineering literature.[8,55–57] Nevertheless, the activities within this step should be targeted to gathering data for the evaluation of sustainability as defined above. That is, the outputs of this step, mass and energy flows including emissions, should be specified to support the evaluation of the sustainability performance of the process alternatives based on the selected indicators.

Case study

Preliminary techno-economic analyses served as a basis to define specific production process alternatives for the case study, exploring the use of various conversion technologies (i.e., direct fermentation (DF) and alcohol to jet (ATJ) for sugar streams, hydrotreated esters and fatty acids (HEFA) for oil streams, and fast pyrolysis (FP), hydrothermal liquefaction (HTL) and gasification Fischer–Tropsch (GFT) for lignocellulosic streams) and pretreatment methods.[13,14] The production scale was defined as 210 kton/year of bio-SAF, aiming to cover 10% of the jet fuel demand of the main airports in Sao Paulo and Rio de Janeiro, assuming 50% blending with conventional jet fuel. Process utilities were considered inside the battery limits increasing mass and energy integration potential.

From this analysis, production chain alternatives were defined as (1) sugarcane processed with ETJ and FP for the sugarcane juice and solid residues fractions respectively; (2) eucalyptus residues processed with FP; (3) eucalyptus residues processed with HTL; (4) macauba processed with HEFA and FP for the oil and solid residue fractions respectively; and (5) macauba processed with HEFA and HTL in the same way. Derived from the combination of feedstocks and conversion technologies, by-products included succinic acid, and energy products like diesel and naphtha, and excess power to be sold to the grid.[10,13,14] The production of hydrogen – a raw material for the upgrading of intermediate streams to jet fuel quality – was initially considered outside of the battery limits. Looking at its impact in the early studies of the project, hydrogen production and its integration with some of the evaluated processes was also studied.

Sustainability evaluation and identification of tensions and opportunities

The evaluation of the process alternatives with regards to sustainability is based on the indicators defined in the Open Sustainability step. A life-cycle approach to the sustainability analysis is suggested, especially for the measurement of environmental impacts for which well-defined methods and tools exist. However, attention must be given to making explicit the underlying uncertainties and assumptions that are part of the analysis (e.g., data sources, allocation methods) given the impact they can have on the evaluation results.[58] For this, the present framework can be aligned with *ex ante* life cycle assessments (e.g., anticipatory LCA, consequential LCA) promoting a discussion with stakeholders about these aspects during the selection of data, the evaluation of alternatives, and interpretation of results.[59]

Evaluation results are contrasted with regards to the different sustainability issues identified in earlier steps of the framework. It is expected that tensions will emerge with regard to different sustainability aspects. As part of the analysis, sustainability tensions are therefore identified and contextualized to identify improvement opportunities, and strategies for further research. If possible, the concepts and the evaluation results are brought for discussion with stakeholders for feedback, potentially providing new insights for their contextualization or the identification of new opportunities, and to deliberate on the sustainability tensions and possibilities for future action with, for example, social learning and responsible innovation tools.

Case study

Figure 1 shows the results related to climate change, energy efficiency and profitability, and Fig. 2 shows the results related to the qualitative exploration of energy security. These results indicate a tension emerging with regards to the production of hydrogen and utilities and the valorization of side streams, and serves to illustrate this step of the framework.

All of the options that were studied led to lower emissions and less energy use than conventional kerosene but at higher cost (i.e., GHG emissions from fossil kerosene are at 87.5 gCO2/MJ[60] while the kerosene price is in the range of 311–722 $/ton looking at the past 3 years.)[61] The alternatives with a higher economic profitability are those based on the processing of lignocellulosic residues. When looking at technology alternatives to process these residues, the most favorable one in economic terms (i.e., HTL) is the least favorable with respect to climate change and energy efficiency. This is largely related to the energy and hydrogen requirements estimated for this alternative.[13,14] An opportunity for resolving this tension is to explore alternative approaches for the generation of hydrogen. Steam methane reforming, considered in the present study, is the most common and economic option but it is one of the main contributors of natural gas and emissions in the case of HTL.[13] Interesting alternatives that can be further explored are, for example, the thermochemical conversion of a fraction of the biomass for producing H_2, or even the electrolysis of water using renewable energy.[62]

However, this path leads to a tension between different product alternatives, each favoring the interests of different stakeholders. Hydrogen from biomass can be favored over higher value products or bio-SAF by dedicating a fraction of biomass or lignocellulosic residues for gasification, and thus improving the non-renewable energy efficiency and climate change impacts of the production chain. This would assist the airlines using this fuel to meet their decarbonization targets and the biorefinery operators' performance in line with the recently passed National Biofuel Policy (RenovaBio) in Brazil through which GHG emission savings can yield a profit for biofuel producers[63,64] (although the added profit from RenovaBio vis-à-vis added capital investment is another point for study). Bioenergy can also be produced through co-generation from a fraction of the biomass feedstock (or residues in the case of ATJ) and in this way

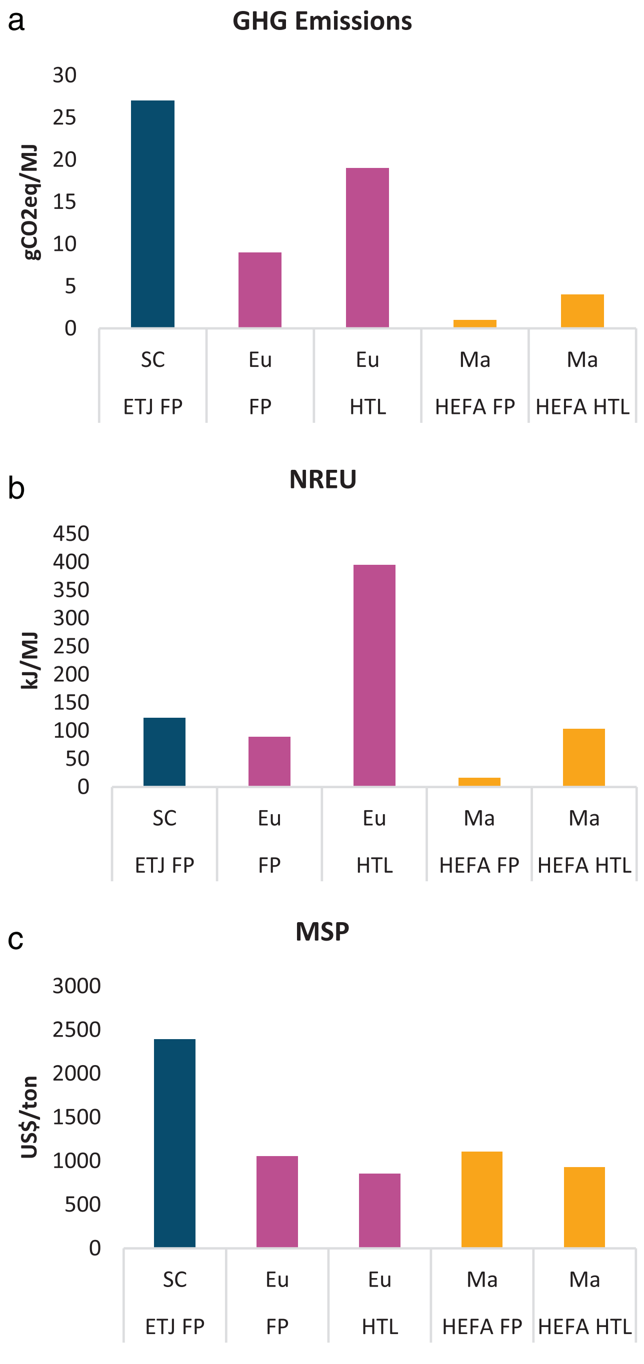

Figure 1. Performance of potential production chains with regard to GHG emissions (a) as indicator of climate change; NREU (b) as indicator of efficiency; MSP (c) as indicator of profitability. ETJ: Ethanol to jet; Eu: Eucalyptus; FP: Fast pyrolysis; GFT: Gasification Fischer–Tropsch; HEFA: Hydro-processed esters and fatty acids; HTL: Hydrothermal liquefaction; Ma: Macauba; SC: Sugarcane.

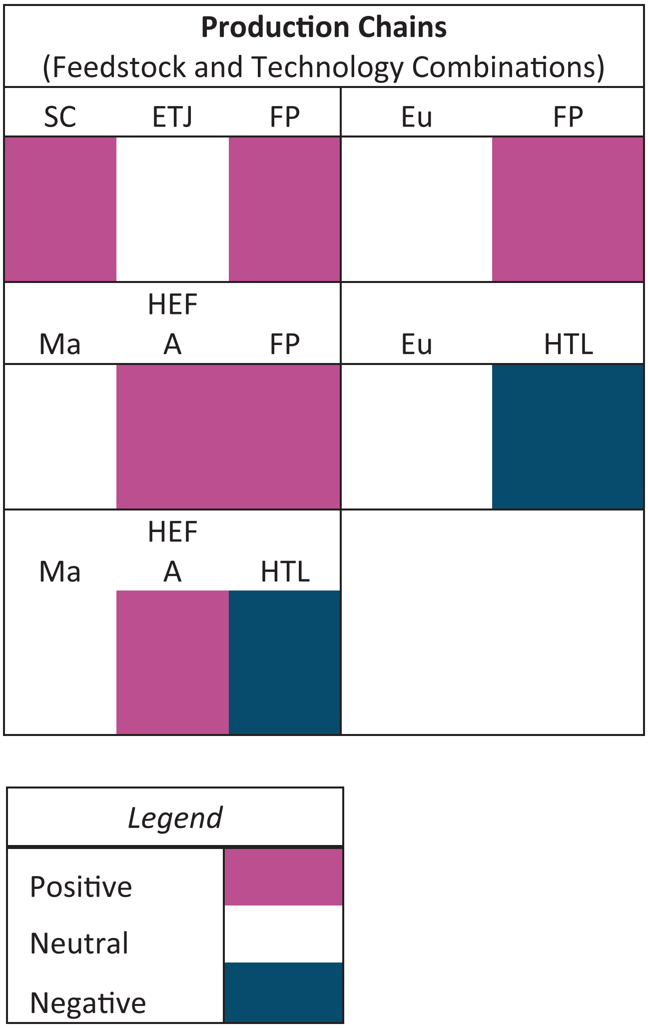

Figure 2. Qualitative comparison of the performance of bio-SAF production alternatives on energy security presented per production chain. Production chains (five in total) are evaluated considering the combination of a feedstock and one or two technologies (3 × 2 or 3 × 3 cells respectively). ETJ: Ethanol to Jet; Eu: Eucalyptus; FP: Fast pyrolysis; HEFA: Hydro-processed esters and fatty acids; HTL: Hydrothermal liquefaction; Ma: Macauba; N/A: Not available; SC: Sugarcane.

can contribute to distributed power generation in the region for the sake of energy security, which is in the interest of the regional government. Higher value products like succinic acid can also be produced from a dedicated part of the feedstock stream, resulting in a much higher profitability potential for the biorefinery operator and investors.[10] All of these options (excluding the processing of residues in ATJ) come at the cost of bio-SAF production capacity per amount of processed feedstock, requiring more feedstock to meet the emission reduction targets of the aviation sector.

Overall, these interests represent sustainability aspects favored by different stakeholders in bio-SAF production in the region.[2] A sustainability analysis on its own cannot indicate which alternative is the best or the worst. Instead, a sustainability analysis that explicitly identifies sustainability tensions, as presented in this work, can contribute to a negotiation process with all stakeholders to define acceptable conditions (e.g., a minimum contribution to the regional power supply per production plant), or even a common objective for developing a production chain.

Discussion and conclusions

The OSiD framework presented here aims to integrate considerations of the local context and stakeholders for an *ex ante* sustainability analysis in the design of biobased processes. The framework was illustrated though extracts from a case study related to the production of bio-SAF. For this, engagements with stakeholders allowed the sustainability analysis to be contextualized, identifying relevant sustainability aspects for the case study and specifying them with regard to the local context. While it was not possible to evaluate all identified sustainability aspects, the recognition of these issues allowed the identification of emerging tensions and opportunities for future work, which are partly presented in this work. However, from the case study presented here it was not possible to engage stakeholders to discuss or evaluate the alternatives presented. Having such an open approach and including stakeholders as suggested in the framework presented here could reduce the ambiguity associated with the diverging values of the stakeholders,[2] and could strengthen the stakeholder network for the development of more sustainable and responsible biobased production.[65,66]

It has to be recognized, however, that there is a methodological tension with the presented framework. The capacity for action is in tension with the available knowledge when analyzing the sustainability impacts of emerging biobased technologies. In the early stages of development there is more space for changing an innovation (e.g., a technology or a crop) in support of sustainability when learning about its performance. This is more difficult at later stages of development as, by then, investments are already in place as, e.g., pilot or demonstration facilities. However, *ex ante* analyses as presented here imply inherent uncertainties related to limited data and knowledge about the performance and consequences of production. For example, in the case study presented here there are uncertainties related to, e.g., production yields and GHG emissions at commercial scale, indirect land use changes, and long-term consequences for the sustainability of soils. This quandary is an instance of the famous Collingridge dilemma, which states that at early development stages of a technology there is limited knowledge about its impacts, but later when it is implemented there is limited capacity to change it.[67]

Possibilities for increasing the predictive capacity of *ex ante* analyses like the one presented here are, for example, incorporating risk analyses to support decision making, as is done in the case of safety risks of nanomaterials.[68,69] In the case of bio-SAF, there are already a few studies looking at the uncertainties associated with aviation biofuel production, mostly focused on economic and technological uncertainties.[10,70] These types of analyses could be further extended to other relevant aspects of a specific biofuel production chain. Another research avenue is to develop the capacity to monitor consequences and change the course of a technology, or production chain as in this case, if it is no longer desirable.[2,71] If possible, combining strategies for increasing knowledge and capacity for action is a way to deal with the limitations of *ex ante* sustainability analyses.

Overall, a novel *ex ante* analysis of the sustainability of aviation biofuel that includes a discussion of sustainability tensions and opportunities for its production in southeast Brazil was presented. This approach may be also applicable to other regions and other production chains in support of a more sustainable transition away from fossil resources.

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