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CHAPTER 10

Sustainability tensions and opportunities for aviation biofuel production in Brazil

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1. Introduction

Biobased production has been promoted as a sustainable alternative to fossil-based production in order to mitigate climate change [1]. Prominent targets for biobased production are fuels and chemicals for which there are limited alternatives, such as aviation biofuels [2]. Biomass is the only current alternative for obtaining these products, however, due to high production costs and limited availability of *sustainable* feedstock, their production remains a challenge [3]. Nevertheless, the CORSIA agreement by the United Nations' aviation agency enforces an international commitment for carbon neutral growth in the aviation sector (relative to 2020), and biobased and other sustainable aviation fuels are critical to achieve this [4].

Concerns over the sustainability of biofuels have been emerging since the production growth in the 2000s [5]. These concerns include effects on food security from the use of edible feedstock, effects of land use changes on emissions, and negative impacts on the livelihood of local communities [5–7]. While not necessarily related to all biofuels, those examples indicate that there are downsides of biobased production as well, and that tensions may emerge between different sustainability aspects, like emission reduction targets and food security impacts. As these tensions depend on local contexts [8], there is a need for comprehensive ex-ante sustainability analyses, taking into consideration the context around biofuel production.

With the growing interest in aviation biofuels, various production alternatives have been developed and assessed, indicating that aviation biofuels have the potential to reduce emissions when compared to fossil-based kerosene [9]. However, existing approaches for the design and ex-ante assessment of biofuel production tend to focus on techno-economic feasibility, climate change, and energy efficiency, and rarely address societal aspects and the

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local context of the intended production chains [10]. Cavalett and Cherubini [11] investigated the impacts of aviation biofuels from forest residues in relation to the UNs Sustainable Development Goals. While their study addresses some societal implications of aviation biofuels, in their analysis not much attention is dedicated to how these goals and their measurement are relevant in the regional setting under study.

Here, we present a novel context-dependent ex-ante sustainability analysis of aviation biofuel production, which includes economic, environmental, and societal aspects. Focused on the Southeast region of Brazil, and based on inputs from local stakeholders and sustainability literature [12,13], eight aspects of sustainability were considered: climate change, commercial acceptability, efficiency, energy security, investment security, profitability, social development, and soil sustainability. For the analysis, we integrate and contrast estimates of the performance of production alternatives with regard to these aspects, which were estimated separately as part of the same research project [12–21]. Based on this contrast, sustainability tensions for the production of aviation biofuel in Southeast Brazil are discussed, and some opportunities for reconciling them in future developments are presented. In view of these findings, we provide conclusions related to the case study and the followed methodology for a more *sustainable* biobased production. Note that the followed methodology and its contribution to the field of sustainable biobased production has been recently discussed by Palmeros Parada et al. [22].

2. Methods

2.1 Production alternatives for aviation biofuel

Possible production alternatives for the case study were based on expected economic potential (the difference between sale revenues from all products and feedstock costs), production yields, and feedstock availability in Southeast Brazil, as described by Alves et al. (2017) [14]. Feedstock materials in consideration were macauba, jatropha, camelina, soybean, sugarcane, sweet sorghum, and the lignocellulosic residues of sugarcane, sweet sorghum, eucalypt, pinus, coffee, and rice. These feedstock materials were selected based on oil/sugar content, land productivity, availability in Brazil, resistance to lack of water or nutrients, production and harvesting cost, potential expansion, amongst others [14]. By-products in consideration included secondary fuel products derived from the process (such as naphtha and diesel). Higher-value biochemicals as by-product alternatives obtained from a dedicated fraction of feedstock stream were evaluated, and included intermediates for bioplastics such as ethylene, lactic acid, and succinic acid [14]. The estimated economic potential was used to narrow the range of feedstock materials to eucalypt residues, macauba, and sugarcane, and higher-value products to succinic acid only. Economic potential results are summarized in Annex 1.

Subsequently, preliminary techno-economic analyses were used to define specific combinations of feedstock and technologies for the case study, based on a production scale of 210 kton/year of aviation biofuel [17,18]. Evaluated conversion technologies for sugar feedstock materials were Direct Fermentation to alkanes (DF) and Ethanol-to-Jet (ETJ). Hydroprocessed Esters and Fatty Acids (HEFA) was considered for oily feedstock materials, and Hydrothermal Liquefaction (HTL) and Gasification Fischer-Tropsch (GFT) for lignocellulosic residues. Pretreatment alternatives were also evaluated for lignocellulosic residues, where lignin was considered for aviation biofuel production through Fast Pyrolysis (FP) and GFT, or for power co-generation. Fermentable sugars from pretreatment alternatives were considered for the production of higher-value chemicals, or for second-generation (2G) ETJ aviation biofuel in the case of bagasse. Bare equipment costs were estimated from literature data for similar technologies [23–27], and taking into account economies of scale. Variable costs were determined from mass and energy balances, using the list of prices in Annex 2. Total capital and operational expenses were estimated based on economic factors [28], which include a capital charge (i.e., annualized capital expenses) for the processing technologies considering a plant life of 15 years. Based on the results of the preliminary techno-economic analysis, the most promising production chains for the sustainability analysis described in the next section were: sugarcane processed with ETJ in combination with FP for bagasse, eucalypt residues processed with either FP or HTL, and macauba processed with HEFA in combination with HTL or FP for macauba residues. The main conversion steps for these production alternatives are summarized in Fig. 1, more process details can be found in Cornelio da Silva et al. (2016) [17] and Santos et al. (2018) [18]. As an exception, Gasification Fischer-Tropsch (GFT) is the technology considered for eucalypt conversion when evaluated for social development. GFT was considered for the social development evaluation because the availability of data and development stage of the technology were considered crucial for the analysis (see below the section on social development).

2.2 Sustainability analysis

The performance of promising production chains was evaluated considering the sustainability framework in Table 1. The sustainability aspects that conform the framework were identified from previous work in the target region [12,13], which includes interviews with stakeholders related to the potential production of aviation biofuel (such as representatives of government bodies and biomass producing organizations), a survey with experts on biofuel production, and a sustainability literature review. The sustainability aspects in this study take as benchmark the definitions from Pashaei Kamali et al. (2018) [12], which are based on G4 Sustainability Reporting Guidelines of the Global Reporting Initiative [29] and the United Nation's Food and Agriculture Organization (FAO) Sustainability Assessment of Food and Agriculture systems [30].

Some of the identified sustainability aspects for this case study were left out of the framework (i.e., accountability, cooperation and leadership, cultural diversity, equity

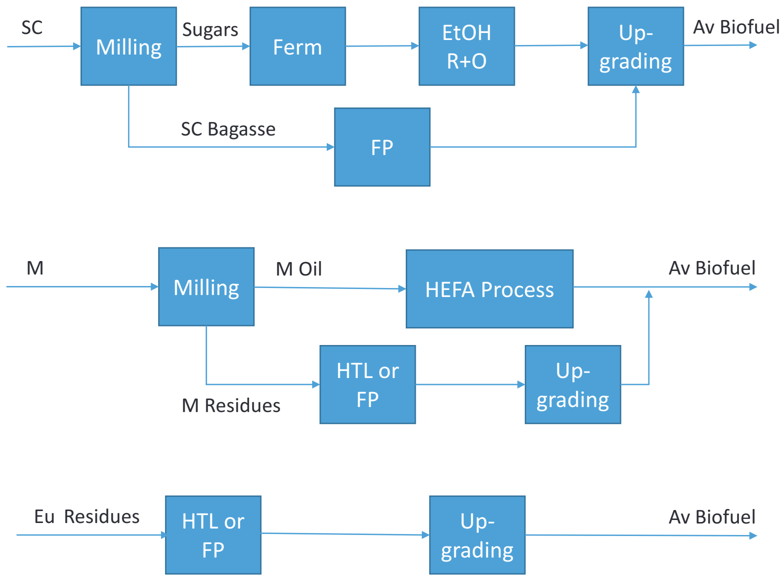

Fig. 1 Evaluated production alternatives as described in the Section 2. *Av*, aviation; *Eu*, eucalypt; *Ferm*, fermentation; *FP*, fast pyrolysis; *HEFA*, hydroprocessed esters and fatty acids; *HTL*, hydrothermal liquefaction; *M*, macauba; *R+O*, recovery and oligomerization; *SC*, sugarcane. For process details see Cornelio da Silva et al. (2016) [17] and Santos et al. (2018) [18].

and social cohesion, human health and safety, labor rights, property rights, participation, rule of law, standard of living, training and education, and working conditions) considering data availability and the design scope of this work. That is, some sustainability aspects are mostly related to the implementation of production and are beyond the scope of design choices, or for their analysis they require monitoring data that was not available (especially for macauba for which there is no commercial full-scale production). Additionally, food security, often discussed in relation to the sustainability of biofuels, was not evaluated given that stakeholders did not consider it a prominent issue in the region [13] (possibly related to reported food production surplus and land availability in Brazil [41]). Perceptions of food security impacts, particularly from international stakeholders related to the aviation sector, did emerge from the interviews and could be analyzed as an aspect of commercial acceptability [13]. However, food security perceptions as part of commercial acceptability, and which are often associated to the use of food crops, were not further investigated given that none of the considered feedstock alternatives are food crops [42]. Nevertheless, given the complexity of this topic, a dedicated study on the food security impacts derived from the use of the considered feedstocks in Southeast Brazil is suggested in future work.

Profitability, climate change, and efficiency impacts were estimated with Minimum Selling Price (MSP, the lowest price at which biofuel can be sold to cover

Table 1 Sustainability framework for the ex-ante analysis of aviation biofuel production in Southeast Brazil.

Sustainability aspects		Description	Indicator(s)	Methods	Main references
Qualitative	Commercial acceptability	Analyzed in relation to ensuring safety and a good performance of aviation biofuel	ASTM approval	Literature review and stakeholder interviews	[13,31,32]
	Energy security	Related to energy supply reliability and self-sufficiency	Potential for power generation and NREU	Literature review and stakeholder interviews	[13, 17, 18]
	Investment security	Related to the readiness level of new crops and technologies, and previous experience with potential crops	FRL and crop development status	Literature review and stakeholder interviews	[3,13,33]
	Soil sustainability	Regarding the protection and recovery of the soil in relation to biomass production.	Residue harvest	Literature review	[15,34–40]
Quantitative	Climate change	Analyzed as the GHG emissions derived from the biomass production and distribution stages, and the aviation biofuel production process	GHG emissions	Life cycle assessment	[16–18, 21]
	Efficiency	Primarily evaluated in terms of nonrenewable energy use and other mass and energy efficiency indicators related to the process	NREU	Process modeling	[17, 18]
	Profitability	Analyzed in terms of the minimum selling price of aviation biofuel required to payback production expenses, including capital and operational expenses	MSP	Techno-economic analysis	[17, 18]
	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	Input-output analysis	[19]

ASTM, American Society for Testing and Materials; *FRL*, fuel readiness level; *GDP*, gross domestic product; *GHG*, greenhouse gases; *MSP*, minimum selling price; *NREU*, nonrenewable energy use.

production expenses as $/ton), GHG emissions (as g CO_2/MJ), and Nonrenewable Energy Use (NREU as kJ/MJ) as indicators. The quantitative results presented in this work are based on the detailed estimations by Cornelio da Silva (2016) for production with eucalypt and macauba using FP, HEFA, and HTL technologies [17]; and on the work by Santos et al. (2018) for sugarcane using ETJ and FP [18]. Additionally, two improvement scenarios for sugarcane are presented based on (i) the co-processing of sweet sorghum during sugarcane off-season with the same equipment and, (ii) the co-production of succinic acid from fermentable sugars [18]. The estimations of MSP, GHG emissions, and NREU in the referenced studies consider the stages of biomass production and transportation, and the conversion and upgrading to bio-kerosene. Since the carbon emitted during combustion is biogenic carbon (i.e., captured during plant growth—photosynthesis) [43], CO_2 emissions from combustion were considered as neutral in the analysis. Considering that the evaluated alternatives are multiproduct systems where most products are energy products (e.g., aviation biofuel, diesel), the allocation method for GHG emissions and NREU between products was based on energy content (economic allocation was avoided due to fluctuating market prices in the energy sector). Additionally, it has been shown that different allocation methods for sugarcane-based production, which includes nonenergy products, lead to the same conclusions in terms of GHG and NREU, differing by less than 5% [18]. Emissions from the agricultural stage are an exception and were allocated based on the economic value of by-products generated at this stage. Energy allocation would neglect differences in wood and wood residue products that have similar energy contents but very different uses and economic value. A system expansion approach was followed for bioenergy as a product, assuming it replaces the generation of power from the Brazilian grid under national mix conditions. With regard to process alternatives, the in-house production of H_2 through steam methane reforming, the heat and power generation from solid residues, and the optional cracking step were considered based on the estimations from Vyhmeister et al. (2018) [20]. However, this work does not refer to specific results obtained in that study as it was based on different indicators. Nevertheless, their conclusions regarding process options are included in the discussion of results as their analysis is based on production chain alternatives similar to the ones considered in this work.

Social development impacts are presented in terms of employment, gross domestic product (GDP), and trade balance contributions based on the macroeconomic Input-Output analysis by Wang et al. (2019) [19]. Effects with regard to these indicators are estimated for the overall economic structure of Brazil as described by the most recent national Input-Output tables [44], and include effects directly related to the production of aviation biofuel, and indirect effects that relate to intermediate inputs and activities that support production. The effects on employment, GDP, and trade balance are presented for three potential production chains as described by Wang et al. [19]: (i) sugarcane-based production with ETJ conversion for sugarcane juice and FP conversion of bagasse;

(ii) eucalypt-based production with GFT conversion; and (iii) macauba-based production with HEFA conversion for macauba oil and FP for residues. GFT is the considered technology because the Input/Output analysis was based on policy and technology development scenarios, for which other technologies were discarded based on data availability and development stage. It is expected that the difference between GFT considered in the social development analysis, and FP and HTL for the rest of the indicators, does not strongly affect the overall comparison considering the large effect of the feedstock production stage on social development impacts, such as employment creation [45]. In the work by Wang et al. (2019), two different estimations are available for the three production chains, differing only on the projected aviation biofuel demand (i.e., 360 kton and 540 kton) [19]. In this work the average of these two estimations of employment, GDP, and trade balance impacts is presented per kton of aviation biofuel (the difference between estimations is less than 3%).

Commercial acceptability, energy security, investment risks, and soil sustainability were qualitatively investigated based on recent literature reports for the considered feedstock and technology alternatives, as seen in Table 1. **Commercial acceptability** was explored as an aspect of the sustainability of aviation biofuel production, and considering the concerns of stakeholders in the aviation sector regarding regulations and safety perceptions [13]. This aspect was explored in terms of the approval status by the ASTM, in alignment with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels [46]. ASTM sets quality standards for "drop-in" aviation biofuels, and certification is granted to a specific aviation biofuel depending on the production processes to obtain it. Certification thus assures that the fuel has the same safety and performance, and can use the same infrastructure as conventional kerosene [47]. To put the results from the exploration of commercial acceptability in a visual form, alternatives that imply ASTM approved technologies were considered as having a positive score. A neutral qualification was given to alternatives with technologies in queue for approval, while a negative score on this aspect was considered for technologies that are not yet in consideration for ASTM approval.

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 energy supply problems in the past [13]. Therefore, to analyze energy security, energy use derived from process simulations 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 NREU and a positive score for the alternative with lowest NREU) [17,18]. The potential of the different alternatives for power generation (expected to contribute to energy reliability [13]) was taken as an indicator of energy security performance related to each feedstock. A positive qualification was given when a feedstock alternative implied the availability of residues for co-generation regardless of the process configuration. A neutral score was considered when availability depended on the process configuration (there was no alternative with a negative effect on this aspect).

Investment security was explored depending on the readiness level of a conversion technology and feedstock. This aspect was considered according to the responses of stakeholders from the government, technology companies, and research institutes. Some of these stakeholders referred to farmers who perceived risk in unproven technologies (including feedstock materials), especially those for which they had no relatable experience [13]. For technology alternatives, the fuel readiness level scale (FRL, 1–9) was used as a reference. FRL is a risk management framework to specifically track the research and development stage of alternative fuels, considering the technology to produce it, manufacturing capacity, and compatibility with existing infrastructure [33]. The analysis takes as reference the conclusions from Mawhood et al. (2016) [3], and it is complemented with more recent information about the considered technologies [31,48,49]. For feedstock biomass, the FRL scale from the Commercial Aviation Alternative Fuels Initiative was used as a benchmark [50], taking recent literature into account [51–54]. Then, a positive score was considered for feedstock biomass that already reached a full-scale commercial deployment, a neutral effect for feedstock biomass in precommercial testing, and a negative one for feedstock biomass at the preliminary evaluation stage.

Soil sustainability was investigated following stakeholders' concerns regarding the protection and recovery of natural resources, especially with regard to deforestation and the degradation of land [13]. Most interviewed stakeholders showed concern about this aspect, including respondents from the government, aviation and technology companies, and research institutes [13]. Soil sustainability was studied through a review of the literature. For sugarcane, a recent and extensive review on the agronomic and environmental implications of residue removal in Brazil [34] was used as main reference for our analysis. For eucalypt, different studies in the context of Brazil [35–40,55] were consulted, as well as other studies regarding forests in other contexts [56–59]. Extensive budgets were made for biomass and nutrients present in the various components of the trees (wood, bark, branches, leaves) depending on stand age, geographic region, and tree species and cultivars [15]. All these factors were of influence on the conclusions on harvest residues. However, as for sugarcane, there were no studies that provide an integral assessment of all components of soil sustainability.

3. Discussion on sustainability performance of production alternatives

In this section, the evaluation of the considered production alternatives is discussed according to the sustainability framework presented in Table 1.

3.1 Quantitative aspects

Climate change. Aviation biofuel produced from macauba oil and residues is estimated to be the least emitting alternative, with about 90% lower GHG emissions when compared to conventional kerosene; eucalypt alternatives are second best with emission savings of 75%–90% (Fig. 2A). For eucalypt, higher GHG emissions were estimated with

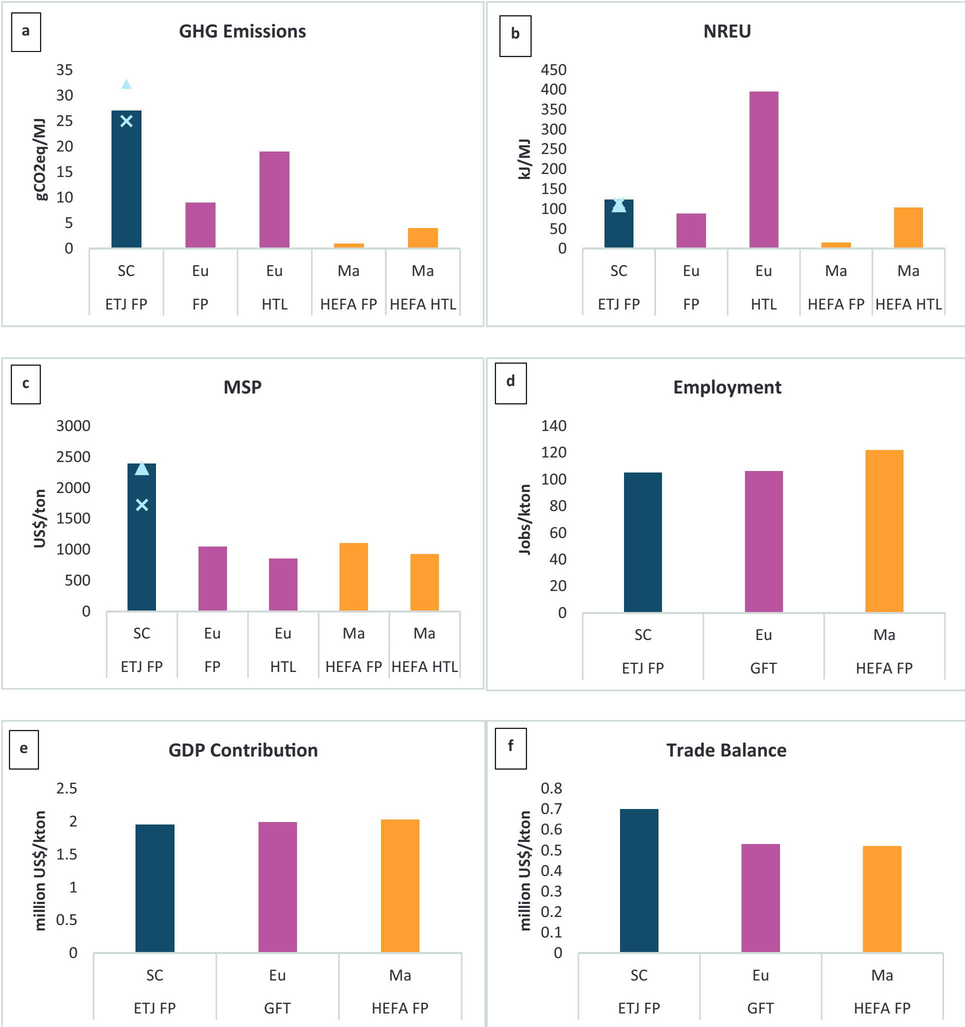

Fig. 2 Performance of potential production chains with regard to GHG emissions (A) as indicator of climate change, with GHG emissions from fossil kerosene at 87.5 g CO_2/MJ [60]; NREU (B) as indicator of efficiency, with 1200 kJ/MJ of NREU required for fossil kerosene production; MSP (C) as indicator of profitability, with conventional kerosene price in the range of 311–722 $/ton the past 3 years [61]; and employment (D), GDP contribution (E), and trade balance (F) as indicators of social development. In A, B, and C a triangle marker (▲) indicates the improvement scenarios with sweet sorghum during sugarcane off-season; a cross (×) indicates the scenario with a fraction of the sugar for succinic acid production. *ETJ*, ethanol to jet; *Eu*, eucalypt; *FP*, fast pyrolysis; *GFT*, gasification Fischer-Tropsch (see Section 2); *HEFA*, hydroprocessed esters and fatty acids; *HTL*, hydrothermal liquefaction; *Ma*, macauba; *SC*, sugarcane.

HTL than FP due to greater natural gas requirements for producing H_2 [17]. Sugarcane-based production results in about 60%–70% lower GHG emissions than fossil-based production depending on the process configuration [18]. In-house power generation and hydrogen production improve the performance on environmental indicators, while a cracking step that increases the production yield has a small impact [20]. A consequential life cycle analysis (LCA), which also takes into account indirect effects such as land use changes and product replacement, indicates that ETJ aviation biofuel from sugarcane juice has a potential for negative emissions of about -10 g CO_2/MJ when assuming the replacement of natural gas power from the grid [21]. While this number does not mean that CO_2 is captured, it indicates a potential for GHG mitigation, or fewer emissions in a context beyond aviation biofuel (i.e., considering power generation for the grid) [16,21]. However, the effects of using by-products beyond the presented production chains, such as the actual provisioning of bioenergy to the regional power system, need to be investigated in more detail.

Energy efficiency. All production chains require lower nonrenewable energy use per unit of aviation biofuel than conventional kerosene. The processing of macauba and eucalypt residues with HEFA and FP is more energy efficient than alternatives with HTL and sugarcane (Fig. 2B). The lower efficiency of HTL compared to FP is due to higher energy requirements for H_2 production [17]. The lower efficiency of sugarcane alternatives is derived from the biomass growth stage, considering that all the energy use from this stage is accounted for the sugarcane feedstock, while for eucalypt it is allocated between by-products (e.g., wood and residues) [17,18]. Regarding process options, in-house power and hydrogen production in thermochemical routes improve the process efficiency, but are economically unfavorable [20].

Profitability. Production based on eucalypt residues and macauba shows a lower minimum selling price, indicating a higher profitability potential than with sugarcane [17,18]. As expected, all alternatives perform worse than conventional kerosene (Fig. 2C). Aviation biofuel MSP from the processing of eucalypt and macauba is in the range of 850–1100 \$/ton. For processing lignocellulosic residues, HTL shows a lower MSP than FP, although the difference is small when compared to sugarcane ETJ conversion (1720–2390 \$/ton). The low profitability potential of sugarcane ETJ is a result of lower conversion yields and the high capital expenses related to the seasonality of sugarcane. In the improvement scenarios, sugarcane ETJ MSP can be reduced by 3%–28% by processing sweet sorghum during sugarcane off-season and by producing higher-value chemicals [18]. However, the estimated MSP for these alternatives remains higher than the MSP for eucalypt- and macauba-based production (Fig. 1C).

Social development. Macauba-based production shows 17% more employment generation than the other crops, while the difference between alternatives is less than 5% in terms of GDP contributions (Fig. 2D and E). For both employment and GDP, direct effects are largely due to feedstock production as expected, and indirect effects are primarily related to the trade sector [19]. When considering that aviation biofuel may displace part of the production of conventional kerosene, an input-out analysis reveals that overall net jobs and added value (i.e., GDP) can be generated by the transition to aviation biofuel [19]. Regarding trade balance impacts, eucalypt- and macauba-based production resulted in about 34% less imports than with sugarcane (Fig. 2F). The difference lies in the larger inputs from the chemical sector associated to the production chain based on sugarcane. Furthermore, based on the existing economic structure in Brazil, it is estimated that more imported goods, such as industrial chemicals, would be required for the production of aviation biofuel than for conventional kerosene [19]. A possibility to avoid this import increase would be to stimulate the national production of (bio-) chemicals together with the development of aviation biofuel. Lastly, these comparisons are made with available data, with macauba production still under development [54]. It can be expected that as macauba production matures, production costs will drop as has already happened with other mature crops, e.g., sugarcane [62]. This possibility needs to be further investigated as macauba-based production could result in lower direct effects on employment and GDP, and trigger different indirect effects than those presented here.

3.2 Qualitative aspects

Commercial acceptability. From the considered alternatives, only HEFA, ETJ, and GFT aviation biofuels have been approved for commercial use by the American Society for Testing and Materials (ASTM, in alignment with the Brazilian National Agency of Petroleum, Natural Gas and Biofuels) [31,46], indicating that these technologies are more commercially acceptable than the other alternatives. FP has been reported to be in queue for certification but no advances have been reported recently [32,63,64], while HTL is the farthest behind [32]. Because certification assures that a fuel has the same safety and performance, and can be distributed and used with the same infrastructure as conventional kerosene [47], the commercial acceptability of HTL biofuel is considered the lowest when compared to the other technology alternatives (Fig. 3). To get ASTM approval, HTL developers have to directly invest in certification. Certification can take 3–5 years and costs 10–15 million dollars on average [32], and for it sufficient volumes for testing are needed. Therefore, certification implies investing time and resources to scale-up the technology [32], which will constrain start-up ventures.

Energy security. Brazilian aviation biofuel production can reduce the need for kerosene imports, with about 20% of kerosene being imported in Brazil (1.3 million m^3 were imported in 2016 [65]). Hence, more significant contributions can be expected from conversion alternatives with higher efficiency, i.e., FP and HEFA (Fig. 3). Significant to the case is the potential to benefit regional power reliability through co-generation from biomass or process residues, considering stakeholders' concerns regarding energy security (i.e., related to past drought-driven power shortages) [13].

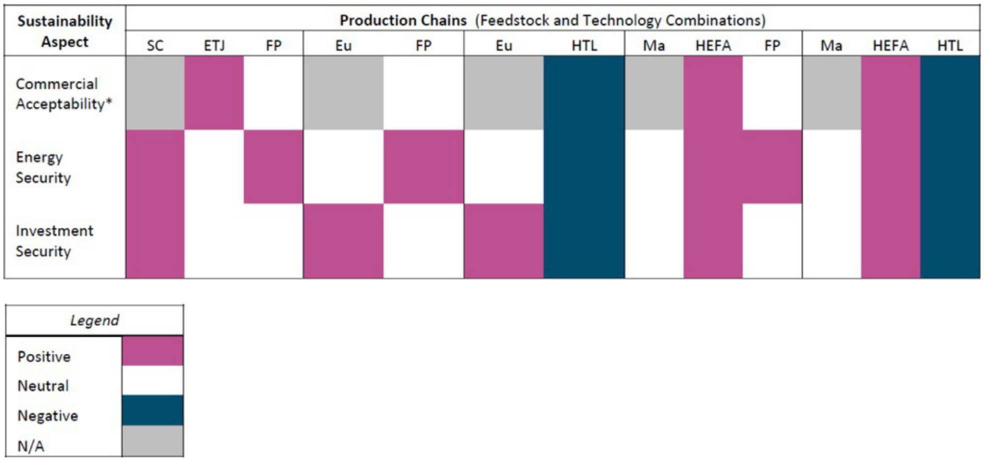

Fig. 3 Qualitative comparison of the performance of the aviation biofuel production alternatives presented per production chain. Production chains (five in total) are evaluated in terms of **commercial acceptability**, **energy security**, and **investment risk**, considering the combination of a feedstock and one or two technologies (3 × 2 or 3 × 3 cells, respectively). The sustainability aspects were analyzed in relative terms as described in the Section 2. *Soil sustainability is not presented as there is not enough data available for a comparison. *ETJ*, ethanol to jet; *Eu*, eucalypt; *FP*, fast pyrolysis; *HEFA*, hydroprocessed esters and fatty acids; *HTL*, hydrothermal liquefaction; *Ma*, macauba; *N/A*, not available; *SC*, sugarcane.

Energy balances suggest that process energy self-sufficiency and power surplus for the grid can be achieved through co-generation from sugarcane residues [18], which is already the case in many sugarcane mills in Brazil [66]. In the case of eucalypt and macauba, a dedicated fraction of the biomass for co-generation would be required to reach energy self-sufficiency, implying a lower aviation biofuel production per amount of processed feedstock [17]. Therefore, sugarcane alternatives are considered as having a relative positive impact when compared to the other feedstock materials (Fig. 3).

Investment security. Investment security was explored in terms of technologies and feedstock biomass. With regards to technologies, HEFA aviation biofuel is the alternative that implies less investment risk with a fuel readiness level (FRL) of up to 8, indicating that HEFA biofuels are certified and commercially available [3]. ETJ fuels recently received ASTM approval, bringing them to an FRL of 7 [31], and slightly behind some HEFA fuels. For FP, there are some ventures in the process of ASTM certification [3,48], indicating a FRL of 6. However, HTL for aviation biofuel production has only been tested at lab scale [49], and it is therefore considered to imply more investment risk at an FRL of 4. For feedstock biomass, investment security was explored in terms of supply certainty and the familiarity of farmers with the crops [13]. Sugarcane and eucalypt, despite not being originally from Brazil, are well established crops in the region, covering developed markets such as sugar, ethanol, charcoal, and wood [51,52], and implying a relatively high investment security. Macauba, although native to Brazil, has not been studied or developed at the same level. Currently, there are a few macauba demonstration plantations being started in Minas Gerais; however, there is still a need for research to develop a production chain (e.g., develop new varieties and plantation management practices) [53,54]. Therefore, investing in macauba in the short term would imply a relatively higher risk for biorefinery operators related to supply uncertainty, as well as for farmers who have neither experience nor access to management practices for production.

Soil sustainability. Soil sustainability was reviewed regarding the effect of residue harvest for biobased production, although there is limited information about macauba (most is known about sugarcane followed by eucalypt). In a recent review where effects of yield, nutrient recycling, soil carbon stocks, GHG emissions, and soil erosion were considered, it was concluded that leaving 7 ton/ha of sugarcane straw is recommendable in order to sustain soil properties [34]. Usually, sugarcane straw yields can vary, as much as 8–30 ton/ha, so it is not simply a matter of leaving half the straw in the field [34]. Remaining straw also comes at a cost, as it may increase certain pests and weeds, and nutrient addition is required as only some 31% of N and 23% of P in the straw will be released for use by plants [34]. Eucalypt, as macauba and other trees, consist of stems, bark, branches, and leaves. The eucalypt wood is 77% of the total tree biomass, but it contains 39% of the nutrients when considering wood and harvest residues together [56]. When stands age, the proportion of wood to total biomass increases, and more nutrients get removed when harvesting, although there are differences among species [35,36] and selection lines within species [37]. Also, the type of residue management in a replanted eucalypt plantation has effects on productivity. For example, 8 years after planting, biomass production was 88% when harvest residues were removed compared to when harvest residues were retained [38], and even decreased to 63% when also the litter was removed [38,39]. Therefore, residue management in tree plantations, such as eucalypt and macauba, appears to be crucial for sustainability. Keeping harvest residues on the fields will be an effective way to maintain soil organic matter levels for all crops. However, in contrast to sugarcane, little information is available on amounts of residues that need to be left behind for eucalypt, and effects depend on the age of the stands when harvested. Recommendations for forests with long rotation cycles range from 20% to 50% of residues and are merely based on expert judgment [57–59]. Therefore, in all cases of biomass production, soil sustainability will depend on leaving behind harvest residues, and further integral studies need to establish rotation lengths and other management practices in order to enhance sustainability impacts.

4. Sustainability tensions and opportunities

Tensions emerge with regard to different sustainability aspects. Prominently, all options yield much lower emissions than fossil-based kerosene but all are more costly (over $300/

ton more than the average kerosene price of the past 3 years [61]). Analyzing the other sustainability aspects reveals other tensions as well. In this section, these tensions and some opportunities for further developments on aviation biofuels in the region are discussed. We discuss tensions related to the technical alternatives for production, to the implementation of production itself, and to the ex-ante analysis of sustainability (Fig. 4).

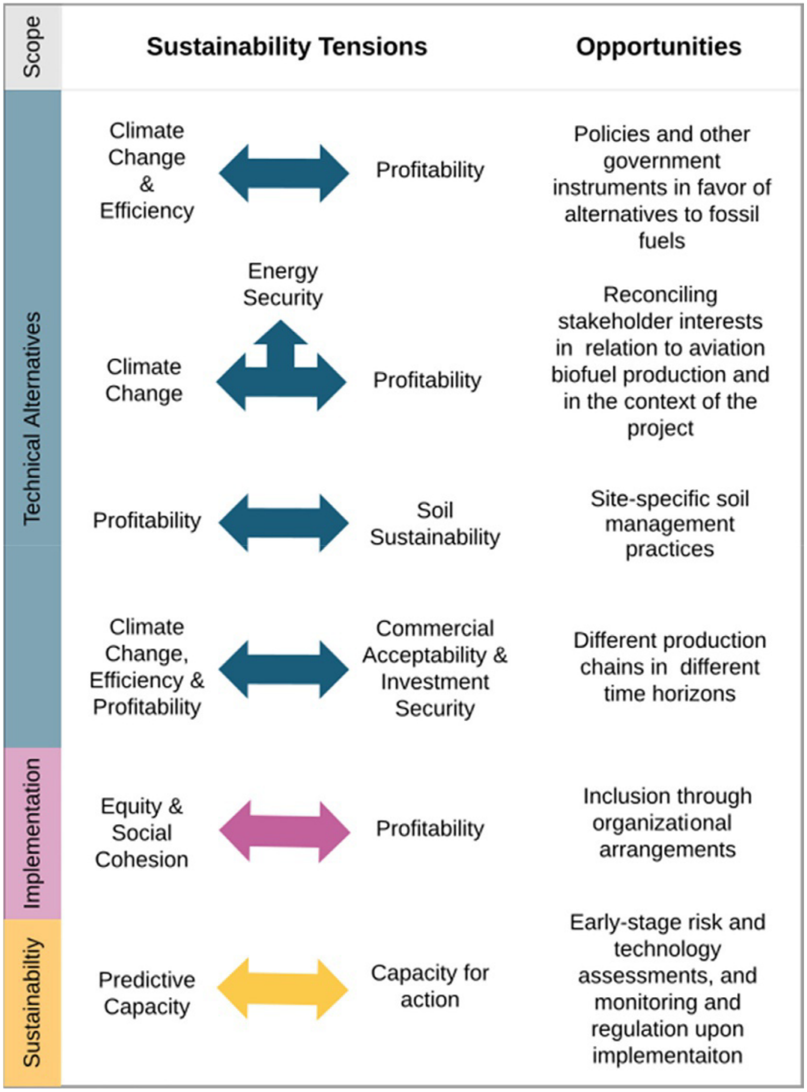

Fig. 4 Sustainability tensions identified for different production alternatives, and identified opportunities in the context of Brazilian aviation biofuel production. Sustainability aspects on opposite sides of arrows are in tension in the context of aviation biofuel production. The *colored column* in the left indicates the scope in which the tension emerges: technical aspects in *blue*, production implementation in *magenta*, and sustainability analysis in *yellow*.

Technology alternatives: Looking at policy contexts. All studied options lead to lower emissions and less NREU than conventional kerosene, however at higher expenses. When looking at technology alternatives to process lignocellulosic residues and produce in-house power and hydrogen, the most favorable alternative in economic terms (HTL) is the least favorable with respect to climate change and energy efficiency. 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 NREU and emissions in the case of HTL [17]. 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 and photolysis of water run on renewable energy [67]. Alternatives for hydrogen production have received substantial attention at the policy level worldwide and in Brazil specifically, with an upcoming National Hydrogen Plan and pilot projects for renewable hydrogen being developed [68].

Furthermore, the presented profitability estimations did not account for GHG emission costs, which have become more relevant since the 2015 Paris Agreement [69]. Prominently, Brazil recently passed the National Biofuel Policy (RenovaBio) to promote the reduction of GHG emissions by the country's fuel sector [70]. As part of this policy, a market for certificates representing GHG emissions savings (relative to fossil fuel emissions) is being launched. Certificates are to be issued by biofuel producers and bought by distributors who have to meet decarbonization targets [71]. As result, GHG emission savings will yield a profit for biofuel producers. Mechanisms like this can therefore open opportunities for aviation biofuels by making them financially more competitive [14,18], especially those biofuels that yield lower emissions (i.e., from macauba with HEFA and FP, and eucalypt with FP).

Technology alternatives: Reconciling stakeholders' interests. A tension emerges between different product alternatives as each favor the interests of different stakeholders: Higher-value products like succinic acid can be produced from a dedicated part of the feedstock stream, resulting in more profitability for investors. However, this option comes at the cost of aviation biofuel production capacity per amount of processed feedstock, requiring more feedstock to meet the emission reduction targets of the aviation sector. Alternatively, power generation can be favored over higher-value products or aviation biofuel by dedicating a fraction or all of lignocellulosic residues for co-generation. Bioenergy can thus be part of distributed power generation in the region for the sake of energy security, as it is in the interest of the regional government. These interests represent sustainability aspects favored by different stakeholders depending on the values and beliefs of the group they represent [72]. Therefore, 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. Such openness and inclusion of stakeholders, with, e.g., social learning and responsible innovation tools, could reduce the ambiguity associated to diverging values of stakeholders [72], and strengthen the stakeholder network for the development of more sustainable and responsible biobased production [73,74].

Technology alternatives: Site-specific soil management practices. A clear tension exists between soil sustainability and harvesting as much biomass as possible for increasing productivity, and thus profitability [15,34]. Defining an optimal amount of residues to leave on the field, as well as other improved practices regarding rotation length, can contribute to solve this tension while also accounting negative consequences of leaving harvest residues in the field (i.e., pest and weed management) [34]. Also, fertilization is needed as in all cases nutrients are removed when harvesting, and not all the nutrients from leftover residues become available to the next crop [34]. However, nitrogen fertilizer is costly in terms of GHG emissions and energy efficiency [75]. Therefore, planning of biomass crop plantations for biofuels requires site-specific recommendations accounting for, e.g., soil type, land surface steepness, climate, length of the rotation, and how these factors influence residue retention and its effect on soil quality and soil functioning, as well as on pest and weed management.

Technology alternatives: Explicit time horizons. Aviation biofuel production based on macauba and eucalypt residues results in more potential benefits in terms of climate change, profitability, and social development. However, they imply a lower investment security than other alternatives. Macauba implies a high investment risk in the short term as production is still under development, and harvest only starts after more than 6 years from planting [76]. Eucalypt, although widely available in the region, implies processing technologies (i.e., FP and HTL) that are still under development, resulting in a lower commercial acceptability and higher investment risks than sugarcane processing technologies.

An opportunity to deal with the tension between climate change, profitability and social development on one hand, and commercial acceptability and investment risk on the other, is to consider the time horizon of projects. Also, it has to be bared in mind that a single crop-and-technology combination does not need to supply all aviation biofuel demand in the region at once. In this way, production based on macauba, with HEFA for processing oil and FP or HTL for residues, could be considered as an alternative in the long term. Sugarcane ETJ and eucalypt FP aviation biofuels could be considered for meeting emission reduction targets in a shorter term. In the case of aviation biofuel from sugarcane juice, the total capital investments could be lower if ethanol mills are already in place, requiring extra capital expenses for ETJ only. This would make sugarcane an easier option. Additionally, the improvement scenarios presented for sugarcane (i.e., production of higher-value products and second crop during off-season) and optimized plantation management options (related to, e.g., nutrient recycling and carbon storage in the soil) could be explored in more detail to improve the system performance on climate change, profitability, and soil sustainability. Nevertheless, stimulating the development of aviation biofuel production implies encouraging producers to switch from their usual crop or product. For example, in the case of sugarcane aviation biofuel, introducing feed-in tariffs in combination with a gasoline tax can encourage its large-scale production and use [77].

Implementation: Organizational arrangements. Although impacts on equality and social cohesion were not evaluated with regard to the different alternatives (see Section 2), a tension between these aspects and profitability was identified during our analysis. In the emergence of production chains for commodity products, like aviation biofuel, economies of scale tend to favor land concentration and vertical integration models (i.e., where the production plant owner also (co-)owns other stages of the production chain, like biomass production) [78]. These production models are in tension with equity and social cohesion aspects since they could lead to the exclusion of smallholders (e.g., family farmers, small-scale local companies) from the production chain [79–81]. An opportunity however, are the business models of nontraditional mill owners, or new entrants, who base their production on arrangements with feedstock producers, as reported for sugarcane expansion areas like Goiás [82]. While new entrants favor these partnership models due to the lower capital requirements for production (i.e., no need to acquire land) [81], these models also open the possibility for the inclusion of smallholder farmers, reconciling aspects of equality and social cohesion with entrepreneurship concerns. To encourage partnership models, there is a need to support organizational arrangements among producers (e.g., cooperatives and farmers associations), and the development of contracts that give revenue certainty to farmers and feedstock security to biorefinery operators [82,83]. While more research is needed in this end, partnership models with such organizational arrangements could result in benefits for rural smallholders with respect to income and stability opportunities, and support the preservation of local knowledge and culture. These outcomes would be an important advantage of aviation biofuels when compared with fossil kerosene.

Sustainability analysis: Knowledge and capacity for action. There is an intrinsic tension when analyzing the sustainability impacts of a technology: In early stages of development, there is more space for improving an innovation (e.g., a technology or a crop) but little information is available; at later stages of development, there is more information about its impacts but it is more difficult to change it. Therefore, 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 this study there are uncertainties related to conversion yields and GHG emissions at large 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 [84].

A straight forward solution to this dilemma is increasing the predictive capacity of ex-ante analyses, for example by incorporating risk analyses to support decision-making, as done for nanomaterials [85,86]. In the case of aviation biofuels, there are already a few studies looking at the uncertainties associated to aviation biofuels production, mostly focused on economic and technological uncertainties [14,87]. This type of analyses could be further extended to cover other relevant aspects of a specific biofuel production chain. A way to deal with knowledge gaps and unexpected events is to develop monitoring schemes along the development and implementation of the technology, leaving the possibility to change its direction [72,88]. Overall, combining strategies for increasing knowledge and capacity for action is a way to deal with the limitations of ex-ante sustainability analyses.

5. Conclusions

We presented 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. Our analysis shows that macauba-based production with HEFA, followed by thermochemical conversion of lignocellulosic residues, performs better than sugarcane alternatives in terms of climate change, efficiency, profitability, and social development. However, choosing the macauba-based alternative over others implies facing a relatively low commercial acceptability and high investment risks. Therefore, we conclude that sugarcane ATJ aviation biofuel is the most opportune feedstock for the production of aviation biofuel in the short term, while eucalypt processing with FP and macauba processing with HEFA and HTL seem as better alternatives in the longer term. To improve the profitability of sugarcane, the production of higher-value products and the processing of a second crop in order to complement off-season production dips will be beneficial. These improvements could be combined with plantation management practices (e.g., optimized nutrient recycling) to ameliorate sugarcane production effects on soil sustainability and GHG emissions, which is applicable to all feedstock biomass. Additionally, to improve the efficiency and climate change performance of thermochemical alternatives, hydrogen generation options based on renewable energy should be explored. As different by-product alternatives can be in the interests of different stakeholders (e.g., improving the economic performance of the production chain or contributing to the energy security of the region), the decision over by-products should be open to participation of relevant stakeholders. With regard to the implementation of production, it was found that producer-operator partnerships can open opportunities for the inclusion of smallholders in the region. Promoting these partnerships and strengthening the role of smallholders through, e.g., organizational arrangements, can serve to bring equality and social cohesion into the development of the production chain. Lastly, we conclude that emerging fuel and carbon policies may provide opportunities for the development of biofuel production.

The presented approach allowed integrating considerations of the local context and stakeholders for an ex-ante sustainability analysis. Engagements with stakeholders allowed to identify relevant sustainability aspects for the case study, and to specify them with regard to the local context. While it was not possible to evaluate all identified sustainability aspects, the recognition of these issues allowed to understand sustainability tensions related to the considered production alternatives, and to identify opportunities for further developments. This understanding will provide a first step toward reducing the ambiguity associated to diverging values of stakeholders, and support the strengthening of a stakeholder network for the development of more sustainable biobased production. For achieving this, social learning and responsible innovation tools can be useful. Overall, the presented approach may be also applicable to other regions and other production chains in support of a more sustainable transition away from fossil resources.

Annex 1 Economic potential (US$ kg^{-1} feedstock) of various production chain alternatives, depending on feedstock type and by-product based on the results in Ref [89].

	Macauba		Jatropha		Camelina		Soybean		Sugarcane		Sweet sorghum	
HVC	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
SA	0.19	0.29	−0.04	0.03	0.15	0.32	0.11	0.28	0.23	0.39	0.21	0.38
ET	0.06	0.15	−0.12	−0.06	0.03	0.20	0.00	0.16	0.06	0.24	0.06	0.23
EtOH	0.00	0.09	−0.16	−0.10	−0.03	0.15	−0.05	0.11	0.00	0.17	0.00	0.16
LA	0.13	0.22	−0.08	−0.02	0.09	0.26	0.06	0.22	0.14	0.32	0.14	0.30
1-BUT	0.02	0.12	−0.14	−0.08	0.00	0.17	−0.03	0.14	0.02	0.20	0.02	0.19
IsoPRO	0.00	0.09	−0.16	−0.10	0.00	0.17	−0.06	0.11	0.00	0.17	0.00	0.16
3-HPA	0.05	0.14	−0.13	−0.07	0.02	0.19	−0.01	0.15	0.05	0.23	0.05	0.22
2,5-FDCA	0.04	0.13	−0.14	−0.07	0.01	0.18	−0.02	0.15	0.04	0.21	0.04	0.20
1,3-PDO	0.06	0.15	−0.12	−0.06	0.03	0.20	0.00	0.17	0.07	0.24	0.06	0.23
1,4-BDO	0.05	0.14	−0.13	−0.06	0.02	0.19	−0.01	0.16	0.05	0.23	0.05	0.22
	Sugarcane residues		**Sweet sorghum residues**		**Eucalyptus residues**		**Pine residues**		**Coffee residues**		**Rice residues**	
HVC	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
SA	0.21	0.37	0.18	0.32	0.21	0.34	0.18	0.31	0.19	0.33	0.19	0.33
ET	0.08	0.23	0.04	0.19	0.08	0.22	0.06	0.19	0.06	0.20	0.06	0.20
EtOH	0.02	0.17	−0.01	0.13	0.03	0.16	0.01	0.14	0.00	0.14	0.01	0.15
LA	0.15	0.30	0.11	0.25	0.15	0.28	0.12	0.25	0.13	0.27	0.13	0.27
I-BUT	0.04	0.19	0.01	0.15	0.05	0.19	0.03	0.16	0.02	0.16	0.03	0.17
IsoPRO	0.01	0.17	−0.01	0.13	0.03	0.16	0.00	0.13	0.00	0.14	0.01	0.14
3-HPA	0.06	0.22	0.03	0.18	0.07	0.21	0.05	0.18	0.05	0.19	0.05	0.19
2,5-FDCA	0.05	0.21	0.02	0.17	0.07	0.20	0.04	0.17	0.04	0.18	0.04	0.18
1,3-PDO	0.08	0.23	0.05	0.19	0.09	0.22	0.06	0.19	0.06	0.20	0.07	0.20
1,4-BDO	0.07	0.30	0.04	0.25	0.08	0.28	0.05	0.25	0.05	0.26	0.06	0.26

Ranges express the minimum and maximum economic potential obtained considering the conversion yields with different technology alternatives.

1-BUT, 1-butanol; *1,3-PDO*, 1,3 propanediol; *1,4 BDO*, 1,4-butanediol; *2,5-FDCA*, ET: ethylene; *3-HPA*, 3-hydroxypropionic acid; *HVC*, High-value chemical; *EtOH*, ethanol; *IsoPRO*, Isopropanol; *LA*, lactic acid; *SA*, succinic acid.

Annex 2 List of prices used for the techno-economic estimations, adapted from Ref. [90], with prices updated to 2015, in US\$ ton^{-1}, and based on the Brazil market, considering crude oil barrel price 64 US\$ bbl^{-1}.

Compound	Price (US\$ ton^{-1})	Specifications[a]	References
Sugarcane	22.3		[91]
Transportation of sugarcane	6.2	10 km with 40 ton truck, bundles density—400 kg m^{-3}	[92]
Sugarcane trash	16.9		
Transportation of sugarcane trash	9.8	10 km with 40 ton truck, bundles density—175 kg m^{-3}	[92]
Sweet sorghum	27.0		[89]
Transportation of sweet sorghum	10.4	22 km 40 ton truck, bundles density—350 kg m^{-3}	[92]
Sweet sorghum grains	78.4		[93]
LPG	234.8	Prices of May 2015	[94]
Naphtha	598.1		
Jet fuel	605.2		
Transportation of jet fuel—Sao Paulo	14.8	150 km with train	[92]
Transportation of jet fuel—Rio de Janeiro	26.6	570 km with train	[92]
Diesel		Price of May 2015	[94]
Acetic acid	672.6		[95]
Furfural	957.5		[96]
S sulfur	151.1		[97]
Lignin[b]	400		Estimated [90]
Sugarcane juice[c]	631.8		Estimated [90]
Transportation of juice (65°Brix)	6.5	20 km with 35 ton tank-truck	[92]
Enzyme for biomass hydrolysis	156.6	Price per ton of ethanol	[98]
Cooling water	0.1		[99]
Chilled water	0.5		[100]
Natural gas	104.7	LHV of CH_4 considered 40.7 MJ kg^{-1}	[101]
Process water	0.25		Estimated [90]
Solids disposal in landfill	0.84		[102]
Operators salary	10.9	US\$ h^{-1}	[103]

Catalysts	Price (US \$ ton^{-1})	WSHV (h^{-1}) w/w	Lifetime (years)	Type	References
Ethanol dehydration	411,905	5 [104]	3	[105]	[106]
Ethylene condensation and oligomerization	252,934	2	5	[105]	[106]

Annex 2 List of prices used for the techno-economic estimations, adapted from Ref. , with prices updated to 2015, in US\$ ton^{-1}, and based on the Brazil market, considering crude oil barrel price 64 US\$ bbl^{-1}—cont'd

Catalysts	Price (US \$ ton^{-1})	WSHV (h^{-1}) w/w	Lifetime (years)	Type	References
Olefins hydrogenation	245,723	3	5	[105]	[106]
Farnesene hydrocracking	39,354	2	5 [107]	[108]	[107]
PSA packing	5079	0.685	3	[102]	[102]
Hydrotreating catalyst	39,354	1st—1.5; 2nd—0.5	2	[109]	[110]
H_2 SMR	38,084	1.4	3	[102]	[102]
Water gas shift	20,315	0.07	3	[111]	[102]
Fischer-Tropsch	15,760	2.22	3	[111]	[111]

[a]Distances are estimated once location of plant is established in Campinas, Sao Paulo. Feedstock transportation distance is estimated with land productivity and average feedstock annual capacity of all scenarios. Transportation method and cost methodology follows from Ref. [92].
[b]Maximum selling price of lignin, considering that it will be sold for a polyurethane manufacturer with a project payback time of 10 years, IRR at 12% and polyurethanes sold at market price.
[c]Maximum selling price of juice, considering that it will be sold to a succinic acid (SA) manufacturer with an annual capacity of 42.3 kton SA yr^{-1},with a project payback time of 10 years, IRR at 12% and succinic acid sold at 2356 US\$ ton^{-1}. Process yields, OPEX and CAPEX methodology follow from *Efe et al.* [112].

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Competing interests statement

The authors declare no competing interests.

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