



# Unpacking bio-based alternatives to ethylene production in Brazil, Europe, and the United States: A comparative life cycle assessment

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## ABSTRACT

Plastics account for 4.5% of global greenhouse gas (GHG) emissions, which are hard-to-abate due to the use of fossil fuels as feedstock. Our study develops a cradle-to-gate life cycle assessment of bioethylene production, exploring 33 pathways across Brazil, the EU, and the US. It aims to understand whether substituting fossil-based ethylene with bioethylene contributes to lowering carbon emissions, and in which of the relevant bioenergy-producing regions/countries the valorisation of biofuels as feedstocks would provide a less carbon-intensive bioethylene production. Results indicate that bioethylene production through catalytic dehydration of sugarcane bioethanol in Brazil presents lowest GHG emission. This pathway could deliver up to  $-2.1 \text{ kg CO}_2\text{e/kg}$  ethylene when accounting for biogenic carbon storage in long-lived applications such as infrastructure. In contrast, beef tallow performs the poorest as a raw material, regardless of whether land-use change (LUC) emissions are considered. When biogenic carbon storage is factored out, none of the pathways outperforms conventional fossil-based steam cracking; however, some are within the fossil-based range indicating potential indirect benefits through reduced refinery utilisation. Our study underscores that biomaterials production as a climate mitigation strategy must be on par with circular economy measures and the conservation of native forestry ecosystems. These results are particularly relevant to policymakers and industries seeking to align polymer manufacturing with sustainability objectives.

## 1. Introduction

Plastics are widely used because they are light, versatile, durable, and relatively cheap. Nevertheless, due to overuse, this material is now a planetary boundary threat, leading to widespread environmental pollution and disruptions in marine ecosystems (MacLeod et al., 2021; Villarrubia-Gómez et al., 2017). Plastics production, which heavily depends on the use of fossil fuels as feedstocks, were responsible for 2

GtCO<sub>2</sub>e or 4.5% of total global greenhouse gas (GHG) emissions in 2015, calling for a comprehensive shift toward low-impact and circular production and consumption patterns (Cabernard et al., 2021; IEA, 2018, 2017; Wit et al., 2019).

High-value chemicals (HVCs) are key building blocks of plastics production. They include ethylene, propylene, butadiene, and mixtures of benzene, toluene, and xylene (BTX), which undergo polymerisation to form plastics. Ethylene stands out for its versatility as a chemical

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intermediate to plastics like polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS) (Geyer et al., 2017). Ethylene is typically obtained through steam cracking of fossil hydrocarbons feedstocks, process in which other HVCs are usually obtained as co-products. Notably, these feedstocks for HVC production – naphtha, ethane, liquefied petroleum gas (LPG), and gasoil – are co-products in petroleum refineries primarily designed to produce transportation fuels such as gasoline, diesel, and aviation kerosene.

This intricate and multi-product supply chain underscores the profound interdependence between fossil fuels and plastics production. Given the environmental implications of this reliance, there is a pressing need to shift from petroleum-derived hydrocarbons to renewable feedstocks. Bio-based feedstocks offer a viable solution by integrating circular economy principles while concurrently reducing GHG emissions associated with ethylene production (Carus and Dammer, 2018; Lange, 2021).

Drop-in ethylene-based bioplastics – identical to their fossil counterparts – emerge as potential alternatives to tackle GHG emissions in the petrochemicals industry in the short- to medium-term (Ali et al., 2023). Bioethylene can be produced from several biomass feedstocks, including starchy, oily, sugary, and cellulosic sources. To produce bioethylene, these feedstocks can be processed via conventional multi-product steam crackers (Oliveira et al., 2021; Pyl et al., 2011) or via on-purpose routes such as the catalytic dehydration of bioethanol (Oliveira et al., 2020; Zhang and Yu, 2013). Yet, bioplastics comprise only less than 1% of global annual plastics production nowadays (Lackner, 2015).

Therefore, integrated biorefineries, which produce both bio-based fuels and plastic feedstocks, may play a critical role in the current climate-driven energy transition (Atiweh et al., 2021). Scaling up production towards large-scale use of biomass for bioplastics production calls for a better understanding of their potential environmental benefits and trade-offs when substituting traditional fossil fuel-based plastics, especially because bioplastics also have been linked to environmental issues like land use change, marine pollution and even higher GHG emissions than their fossil-based counterparts (Atiweh et al., 2021).

Life Cycle Assessment (LCA) is a valuable tool for evaluating the environmental impact of bioethylene through different pathways compared to traditional fossil ethylene, aiding in informed policy-making. Here we focus in three countries that have the potential to capitalize from biorefineries since they are the three largest biofuels producers in the world: Brazil, Europe, and the United States (US) (IEA, 2022a). Brazil hosts the world's first bioethylene plant, set up in 2010, recently expanded to operate at a capacity of 260 thousand tonnes yearly (Braskem, 2023; Schill, 2010), after decades of sugarcane ethanol production in the country (IRENA-IEA-ETSAP, 2013). In Europe, there are over 300 materials- and chemicals-oriented biorefineries, including flagship and demonstration units (European Commission, 2022). And in the US, the “Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program” offers loans to support the development, construction, and retrofitting of technologies comprising advanced biofuels, renewable chemicals, and bio-based products (USDA, 2022).

Previous LCA studies have contributed with valuable insights on the environmental performance of bioplastics production (Walker and Rothman, 2020). For instance, Hong et al. (2014) evaluated corn- and cassava-based routes via ethanol dehydration in China and concluded that the use of corn leads to fewer climate change impacts. Liptow et al. (2015) assessed pathways via wood gasification and wood fermentation in Sweden, showing that the former leads to lower GHG emissions, with both pathways outperforming conventional sugarcane fermentation (Liptow et al., 2015). Alonso-Fariñas et al. (2018) analysed poplar-based pathways via direct and indirect dehydration of ethanol and through dimethyl ether (DME) synthesis, with results indicating GHG emissions reductions in all three cases relative to conventional fossil-based pathways, and better performance of the DME-to-ethylene route

(Alonso-Fariñas et al., 2018). Yang et al. (2018) evaluated corn stover- and corn grain-based pathways via ethanol dehydration, with both cases resulting in fewer emissions than ethylene from ethane-rich shale gas, with the former showing better performance (Yang et al., 2018).

Additionally, several studies include the production of final polymers within the LCA boundaries. An assessment of the US supply of low-density polyethylene (LDPE) – via ethanol dehydration followed by ethylene polymerisation – from US corn, US switchgrass, and Brazilian sugarcane, resulting in the lowest GHG emissions for switchgrass, followed by sugarcane and corn products. Only switchgrass and sugarcane routes result in fewer emissions than fossil pathways (Posen et al., 2015). An analysis of the European supply of high-density polyethylene (HDPE) using Brazilian sugarcane ethanol showed 140% reduction in GHG emissions compared to fossil HDPE (Tsiropoulos et al., 2015a). In Belgium, HDPE from sugar beet and wheat via ethanol dehydration followed by ethylene polymerisation reduced approximately 60% in the climate change impact category in comparison with fossil HDPE (Belboom and Léonard, 2016).

Therefore, past LCA research has shed light on the environmental performance of bioplastics production. Several studies use ethylene as the functional unit, given its relevance as a chemical building block for many polymers. However, comparing results is challenging due to different raw materials, technological routes, geographical locations, and system definitions. In this sense, three main research gaps may be highlighted:

Firstly, many of these studies have a limited scope, as they do not comprehensively analyse various raw materials, feedstocks, conversion pathways within a single study. Moreover, although the literature addresses production across different regions, there is a lack of a single study that consistently incorporates regional specificities under the same functional unit. Emissions stemming from land-use are specific to particular geographic contexts and are also rarely discussed.

Secondly, while previous LCA studies have briefly discussed methodological approaches to account for biogenic carbon storage of bioplastics, they have not necessarily delved deep across a wide range of pathways. In addition, discussions regarding the applications of plastics and their associated age cohorts are rarely addressed.

Lastly, a broader and integrated perspective, one that considers energy and materials production in integrated biorefineries, is missing. The implications for overall system efficiency and optimal resource allocation in bio-based processes are scarcely explored. This omission leaves a gap in understanding what are the opportunities offered by different pathways and where strategic planning can promote synergies between biofuel and biomaterials production.

Our study seeks to bridge these gaps by offering an extensive cradle-to-gate attributional LCA of bioethylene production. We explored 33 production routes across Brazil, Europe, and the US, to analyse: (i) under which conditions the substitution of fossil-to bio-based ethylene contributes to lowering carbon emissions, and (ii) in which region/country the valorisation of biofuels as feedstocks would provide a cleaner bioethylene production and under which conditions/premises. Most of all, this study aims to provide insights for bio-based solutions to global energy and materials transitions.

From here onwards this paper is structured as follows. Section 2 presents the goal and scope of the LCA, followed by the life cycle inventory methodology. Results are presented in Section 3 and further discussed in Section 4. Finally, Section 5 synthesises the main findings and presents final remarks and recommendations for future studies.

## 2. Life cycle assessment method

### 2.1. Goal and scope definition

The main objective of this study is to assess the GHG emissions performance of biomass use as feedstock for ethylene-based plastics. Biomass have higher oxygen content compared to fossil feedstocks,

which facilitates its chemical conversion to carbonates, esters, and chemical platforms derived from bifunctional acids. While these chemicals can provide similar, same and even improved functionalities compared to the olefins-based counterpart, we argue that in the short-to medium-term decarbonisation in the ethylene supply chain is necessary. Ethylene-based chemical facilities and products' market are already in place in large-scale plants and associated with an established value chain that can last for the next two decades, at least. Therefore, we defined 1 kg of ethylene as the functional unit.

In this sense, this study aims to assess the GHG emissions footprint from cradle-to-gate bioethylene routes from crops produced on a large scale and in relevant bioenergy production countries/regions. We performed an LCA to evaluate the GHG emissions of producing bioethylene from seven raw materials in Brazil, Europe, and the US. The LCA method was based on ISO14040 and 14044:2006 standards in a cradle-to-gate approach (ISO, 2006a, 2006b). We assumed 1 kg of bioethylene as the functional unit. The system boundary comprises all stages from cradle-to-gate, meaning from the farming phase to ethylene synthesis, thus excluding actual plastics production, use, and disposal stages.

In this paper, the three terms "raw materials" (a), "intermediates" (b), and "feedstocks" (c) are defined as: (a) agricultural products with little or no processing; (b) the products resulting from raw materials processing; (c) the substances directly consumed by the chemical sector to produce ethylene and co-products, respectively. Fig. 1 shows a schematic representation of the system function and system boundaries, covering both upstream and downstream processes. Therefore, the LCA modelling encompasses four phases: (i) farming phase, i.e. production and harvest of raw materials; (ii) intermediate production phase, i.e. conversion of raw materials into intermediates; (iii) feedstock production phase, i.e. conversion of intermediates into chemical feedstocks; and (iv) ethylene production phase, i.e. chemical processing of feedstocks into ethylene and co-products.

The analysis was performed with the SimaPro 9.2 software with the support of the Ecoinvent 3.7.1 database (Wernet et al., 2016) tailored to reflect specificities of each technological route and different regional contexts. Climate change impact assessment results are reported according to the global warming potential factors from the IPCC Working Group I Sixth Assessment Report with a term of 100 years (GWP 100).<sup>1</sup> Results were also compared with cradle-to-gate GHG emission of conventional fossil-based ethylene from naphtha and ethane steam cracking, based on figures from the literature (Ghanta et al., 2014; Keller et al., 2020; Yang and You, 2017).

## 2.2. Life cycle inventory data

We assessed seven raw materials for the synthesis of ethylene using four conversion pathways in Brazil, Europe, and the US. The combination of raw materials and LUC emissions scenarios, regions, feedstocks and ethylene production technologies led to a total of thirty-three production routes, summarised in Table 1. The subsections below provide further description about each route.

### 2.2.1. Production of agricultural raw materials

We analysed the production of raw materials in Brazil, Europe, and the US. In Brazil, we considered soybean, meat cattle (i.e. through its by-product, beef tallow), eucalyptus, sugarcane, and corn. In Europe, sugar beet and wheat were evaluated. Lastly, we analysed the production of corn in the US. Our selection of these raw materials and regions was defined by their current global relevance in the production of biofuels and biomaterials (FAO, 2021a).

The life cycle inventory data, along with a detailed explanation of our assumptions of the farming phase, is summarised in Table 1

Supplementary Material (SM). All data is presented as a function of 1 metric tonne of raw material.

### 2.2.2. Conversion pathways: production of intermediates and feedstocks

The processes which convert raw materials into intermediates and then to feedstocks are depicted in Figs. S1–S4 in the SM. These figures correspond to the Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch Biomass-to-Liquids (FT-BtL), sugar crop fermentation to ethanol synthesis and Alcohol-to-Jet (AtJ) pathways, respectively.

The HEFA pathway is a lipid conversion process that converts triglycerides found in vegetable oils and animal fats to produce liquid paraffinic hydrocarbons through hydrogenation, isomerisation and hydrocracking. It has been considered as a key pathway to produce sustainable aviation fuels (SAF), which also yields other bio-based co-products such as naphtha, LPG and gasoil (i.e., diesel) (Tao et al., 2017). In this study, these co-products were assessed as potential feedstocks for ethylene and other HVC production. Tables S2 and S4 in the SM present the life cycle inventory for soy oil and beef tallow, and for the HEFA process, respectively.

The Fischer-Tropsch Biomass-to-Liquids (FT-BtL) route converts syngas – a mixture of carbon monoxide and hydrogen – derived from lignocellulosic biomass, into liquid paraffinic hydrocarbons (Tagomori, 2017). In this study, we assessed the use of eucalyptus wood residue as a raw material, which undergoes a pre-treatment process and then gasification to produce syngas. The configuration of the FT-BtL process considered for this study is optimised for producing gasoil as its primary product, while also yielding bio-based naphtha and LPG. All three products were considered as feedstocks for ethylene and other HVCs production. Table S4 in the SM contains the life cycle inventory data for FT-BtL. For being a major soybean, meat cattle, and eucalyptus producer, all these raw materials were analysed considering production in Brazil (FAO, 2021a).

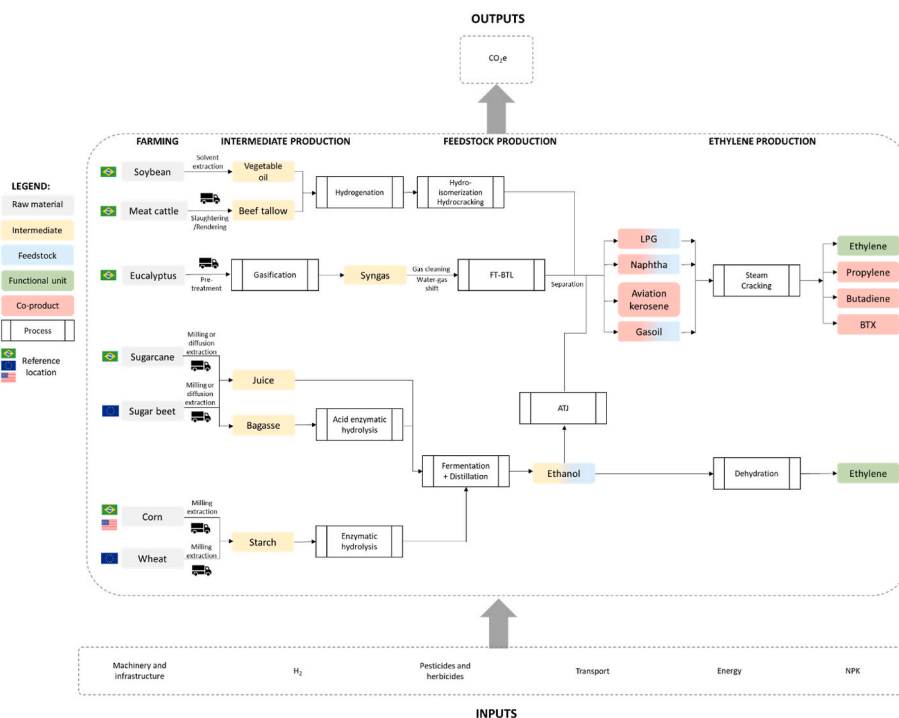
Lastly, the ethanol-based pathways can use different sources of biomass (Pechstein and Kaltschmitt, 2018). We considered: (i) sugar crops, i.e., sugarcane in Brazil and sugar beet in Europe; (ii) starch crops, i.e. corn in the US and Brazil, as well as wheat in Europe; and (iii) lignocellulosic raw materials, i.e., sugarcane bagasse in Brazil. These raw materials contain sugars that are directly extracted (e.g., sugarcane), or produced via enzymatic hydrolysis of polysaccharides (e.g., corn, wheat, bagasse). The sugar solution is fermented to ethanol, which can be used directly as feedstock for ethylene production or as an intermediate in the Alcohol-to-Jet (AtJ) pathway. AtJ dehydrates ethanol to ethylene which is then oligomerized and hydrogenated into liquid paraffinic hydrocarbons, being aviation kerosene the primary product (Geleynse et al., 2018). Similarly, to the HEFA and FT-BtL cases, all relevant coproducts were considered as chemical feedstocks in the AtJ pathway. Tables S3 and S4 in the SM present the life cycle inventory data for ethanol production processes and AtJ pathway, respectively.

Although fossil fuel-based naphtha is currently the main petrochemical feedstock worldwide, LPG and gasoil are also used as alternatives in specific circumstances (e.g., when prices are competitively lower than naphtha). We assume that in scenarios where biorefineries platforms become critical to decarbonising the aviation sector, bio-LPG and bio-gasoil can be used as chemical feedstocks.

### 2.2.3. Production of ethylene

In this study, we considered two technologies to produce ethylene: (i) steam cracking, which uses bio-based paraffinic hydrocarbons as feedstock and (ii) ethanol dehydration, which uses bioethanol as feedstock. Steam cracking is a thermochemical process that subjects the feedstocks to high-temperature heat in the presence of steam to break paraffins into olefins, primarily ethylene, propylene, butadiene, and BTX, along with other fuel by-products. Ethanol dehydration is a catalytic on-purpose process that is considered an alternative to steam cracking. It converts ethanol to ethylene, and unlike steam cracking, it does not produce any other HVCs as co-products.

<sup>1</sup> IPCC AR6 metrics of global warming potential of 100 years (GWP100) timeframe are 28 for methane and 273 for nitrous oxide (Förster et al., 2021).



**Fig. 1.** Life Cycle Assessment scope for bioethylene production. The dotted lines indicate the system boundaries considered in the cradle-to-gate analysis. A detailed description of the raw materials and processes along with the life cycle inventory is described in the Supplementary Material.

**Table 1**  
Evaluated pathways to ethylene production.

Country/Region	Pathway	Agricultural raw materials	Intermediates	Feedstocks	Ethylene production technology
Brazil	HEFA	Soybean*	Soy oil	LPG, naphtha, gasoil	Steam cracking
Brazil	HEFA	Meat cattle*	Beef tallow	LPG, naphtha, gasoil	Steam cracking
Brazil	FT-BtL	Eucalyptus wood	Syngas	LPG, naphtha, gasoil	Steam cracking
Brazil	Ethanol synthesis	Sugarcane	–	Ethanol	Ethanol dehydration
Europe	Ethanol synthesis	Sugar beet	–	Ethanol	Ethanol dehydration
Brazil, US	Ethanol synthesis	Corn	–	Ethanol	Ethanol dehydration
Europe	Ethanol synthesis	Wheat	–	Ethanol	Ethanol dehydration
Brazil	Ethanol synthesis	Sugarcane (bagasse)	–	Ethanol	Ethanol dehydration
Brazil	AtJ	Sugarcane	Ethanol	Naphtha, gasoil	Steam cracking
Europe	AtJ	Sugar beet	Ethanol	Naphtha, gasoil	Steam cracking
Brazil, US	AtJ	Corn	Ethanol	Naphtha, gasoil	Steam cracking
Europe	AtJ	Wheat	Ethanol	Naphtha, gasoil	Steam cracking
Brazil	AtJ	Sugarcane (bagasse)	Ethanol	Naphtha, gasoil	Steam cracking

Source: Own elaboration. \*Soybean and meat cattle production were analysed in scenarios both with and without LUC emissions.

Table S5 and Figs. S5 and S6 in the SM present the life-cycle inventory and the flowcharts depicting steam cracking and ethanol dehydration technologies, respectively.

### 2.3. Uncertainty analysis

The uncertainty analysis implemented in this study uses the Monte Carlo approach embedded into SimaPro 9.2 to estimate the uncertainties in the LCA results, namely the GWP100 values. The method involves changing process inputs randomly by a set number of times (e.g. 1000 steps) within a specified range (minimum and maximum) with a defined statistical distribution for data (triangular in this case). This type of analysis in LCA is usually made to compare deterministic, specialist driven results, to probabilistic, literature driven ones.

The main outcomes of our uncertainty analysis include the median and the cumulative uncertainty in the LCA model, taking account the ranges of selected input variables from the existing literature. In this research, we only assessed uncertainty related to crop yields and farming inputs, such as nitrogen fertiliser, lime application, and diesel

consumption. The extraction and ethylene synthesis stages are well-established, while the production of distillates is still in the development phase. Therefore, we assume that is reasonable that the farming stage carries the greatest uncertainty. This variability comes from many factors including the producer, geographic region, country, season, and climate events, among others.

We conducted the Monte Carlo simulation over 1000 iterations, to achieve a 95% confidence interval for each ethylene production route and feedstock option.

### 2.4. Key assumptions on land use change emissions, allocation criteria, and plastics end-of-life

In the context of climate change mitigation, assessing the emissions from land use change (LUC) in bio-based products is pivotal (IPCC, 2019). Over the past 20 years, soybean and cattle expansion in Brazil were highly associated with deforestation and the removal of native vegetation (Rajão et al., 2020; Soterroni et al., 2019). This has drastically changed the carbon content of soils, which in turn substantially



affected the emissions profiles of the raw materials assessed in this study, especially products derived from cattle and soybean.

Therefore, we specifically estimated direct LUC emissions linked to soybean cultivation and beef tallow production. Our methodological approach incorporated the mean values of direct land-use change (LUC) extracted from the Brazilian Land Use Change (BRLUC) model, developed by *Empresa Brasileira de Pesquisa Agropecuária* (Embrapa) (Novaes et al., 2017). The BRLUC model considers historical and regionalised data from 1999 to 2018 for Brazil. As a comparative exercise, we also assessed Brazilian soybean and beef tallow routes without LUC emissions, termed the “no LUC” scenario. This comparison is designed to underscore the sensitivity of results due to the contribution of LUC emissions to the final GWP100 results of bioethylene production. Notably, in the “no LUC” scenario, no high-carbon lands are directly or indirectly displaced.

Furthermore, and within the scope of our LCA, we took into account critical land use-related emissions. Specific considerations included direct and indirect nitrous oxide emissions resulting from the application of synthetic nitrogen fertilisers, CO<sub>2</sub> emissions resultant from limestone application, and emissions derived from agricultural residues were exogenously calculated and included in the model. Furthermore, when evaluating tallow-based routes, methane emissions stemming from cattle production were factored in.

For multi-product outputs, we employed a physical allocation system grounded in either the energy content as indicated by the low-heating-value (LHV) or the mass content. This approach was used to evenly distribute input requirements and environmental burden between the primary product and the associated by-products. In the farming phase, following a conservative approach, we made no allocations for agricultural residues, assuming that such materials are retained in their original farming fields.

It is also essential to acknowledge that the end-of-life stage was excluded from our system boundary. Thus, to account understand the role of biogenic carbon storage and building on previous work by Oliveira et al. (2021), we analysed two scenarios: (i) *without credits*, where the biogenic carbon gets re-released into the atmosphere post-usage, and (ii) *with credits*, in which the biogenic carbon remains sequestered for prolonged periods.

### 3. Results

Section 3.1 presents a contribution analysis of the farming, intermediate production, feedstock production, and ethylene production phases to the GHG emissions of each of the thirty-three bioethylene production routes assessed. As expected, the farming phase is a major contributor to GHG emissions, and therefore we analysed this phase in more depth. Section 3.2. summarises the assessment of the GHG emissions for each ethylene production pathway analysed.

#### 3.1. Contribution analysis

##### 3.1.1. Overall phase contribution

Fig. 2 illustrates the contribution to total GHG emissions of each of the four stages of the LCA to the cradle-to-gate.

Legend - FT-BtL: Fischer-Tropsch Biomass-to-Liquids. HEFA: Hydroprocessed Esters and Fatty Acids. AtJ: Alcohol-to-Jet. No LUC: Alternative values for soybean and cattle feedstock routes disregarding direct land use change emissions. BR: Brazil. EU: Europe. US: United States.

In 20 of the 33 bioethylene pathways, the farming phase holds the highest contribution to GHG emissions, regardless of the inclusion or exclusion of LUC emissions (i.e., in the case of soybean and beef tallow in Brazil). The intermediate production phase follows as the second-largest contributor in 10 out of 33 pathways, while the feedstock production phase contributes the most in 3 pathways only. For the FT-BtL eucalyptus routes, the contribution of each phase is balanced (around 30% weight to each), though feedstock production exhibits a slightly higher emission profile. As expected, AtJ-advanced sugarcane pathways reveal a low contribution from the farming stage and indicate a larger emission contribution from the intermediate production and feedstock production phases due to the utilisation of residues as raw materials. Similarly, AtJ-sugar beet and wheat pathways also present a relatively higher contribution from the intermediate production phase to total GHG emissions.

For pathways that include steam cracking process, the difference in GHG emissions contribution relates to the type of raw materials rather than the feedstock production phase (whether FT, HEFA, or AtJ). For instance, the GHG emissions profile across different phases in ethylene production from soybean remain similar irrespective of whether the

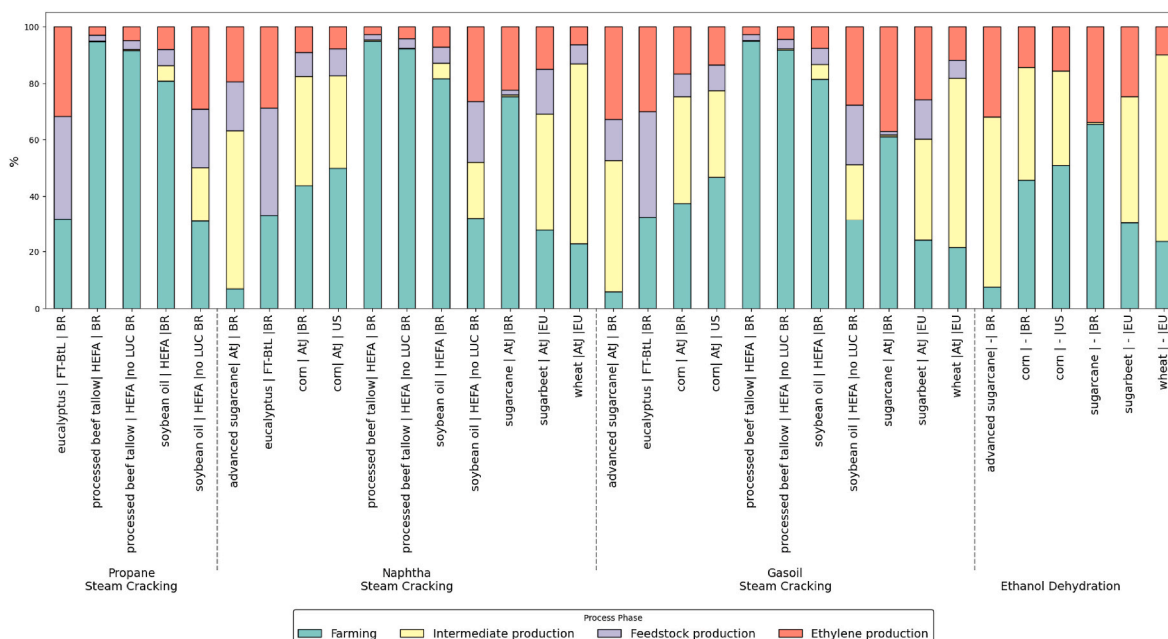


Fig. 2. Contribution of each phase in cradle-to-gate GHG emissions of ethylene production routes.

feedstock input to the steam cracking is propane, naphtha, or gasoil.

Another interesting finding from these set of results is that, despite the ethylene production phase being an energy-intensive process, its overall contribution remained relatively low. However, in pathways utilising raw materials with higher productivity — and consequently lesser energy and fertiliser intensity per kilogram in the agricultural phase — its contribution increased, accounting for up to 37%.

### 3.1.2. Farming phase contribution analysis

In this study, the farming phase emerged as the most environmentally impactful in most of the bioethylene pathways. To better understand this impact, we examined all the inputs associated with each raw material and their respective GHG emissions, illustrated in Fig. 3. For better visualisation, we omitted inputs contributing less than 1% of total GHG emissions.

As expected, N fertiliser inputs prominently influence the emissions profile of most raw materials. This is evident both in upstream (i.e., ammonia production through steam methane reforming and Haber-Bosch synthesis) and downstream (i.e.,  $N_2O$  emissions from fertiliser application) emissions. Together, N fertiliser-related emissions constitute a substantial proportion of the total GHG emissions: 67% for Wheat EU, 48% for Corn BR, 46% for Sugar beet EU, 40% for Corn US, and 24% for sugarcane BR. Emissions for other raw materials range between 3% and 6%. It should be noted that soybean production considered in this study does not use N fertiliser.

Diesel consumption for agricultural machinery also significantly impacts the total GHG emissions, accounting for as much as 53% in the case of eucalyptus production. Lime, akin to N fertiliser, impacts emissions both upstream and downstream, with the latter being significantly larger. For instance, downstream emissions from lime represent over 30% of the total emissions for Corn US.

Other process worth mentioning is enteric fermentation, which is specific to cattle production and contributes to nearly 50% of GHG emissions associated with beef tallow. Moreover, when factored in, LUC emissions constitute over 90% of the GHG footprint for soybean production and 40% for beef tallow.

## 3.2. Comparison of bioethylene production pathways

Fig. 4 synthesises results for overall GHG emissions results of

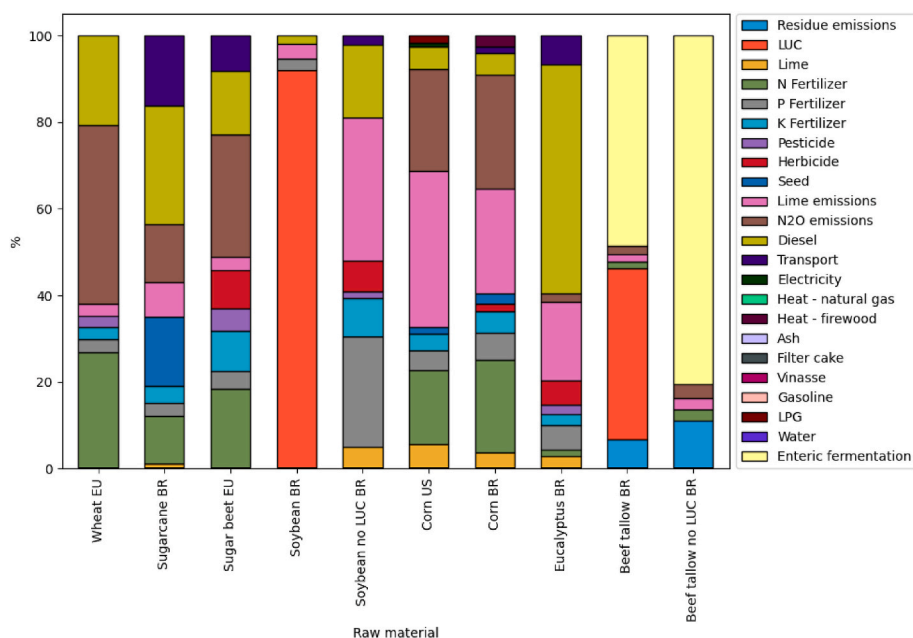


Fig. 3. Contribution analysis for the farming stage. Inputs that contributed to less than 1% of total GWP100 were omitted.

bioethylene production, subdivided by ethylene synthesis pathway – as bio-based propane (LPG), naphtha or gasoil steam cracking, and ethanol dehydration. For each pathway, we present results with (green bar) and without (grey bar) credits for biogenic carbon storage in bioplastics. GHG emissions of ethylene produced via naphtha and ethane steam cracking were used as the fossil fuel-based reference for comparison (1.61 and 0.84 kg  $CO_2e/kg_{ethylene}$ , respectively), which is based on figures from the literature (Ghanta et al., 2014; Keller et al., 2020; Yang and You, 2017).

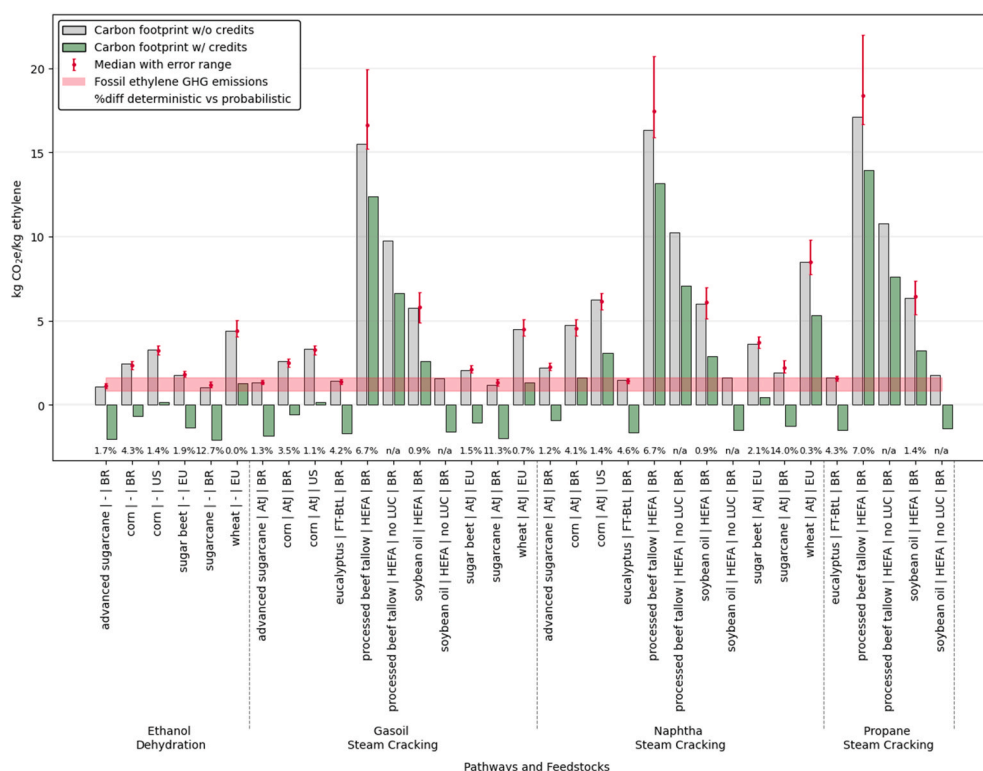
Results show that the ethanol dehydration process using sugarcane ethanol exhibits the lowest greenhouse gas (GHG) footprint at 1.04 kg $CO_2e/kg_{ethylene}$ , while the propane steam cracking with processed beef tallow via HEFA demonstrates the highest footprint at 17.10 kg $CO_2e/kg_{ethylene}$ . When accounting for  $CO_2$  storage, these same processes maintain their positions as the lowest and highest GHG footprints, but their values shift to  $-2.10$  and  $13.97$ , respectively. Below, we analyse the results according to raw materials, ethylene production processes and regions.

### 3.2.1. Raw materials

Results showcase varying GHG emissions across different bio-based pathways. Notably, without considering biogenic carbon storage, none of the assessed pathways presented life cycle GHG emissions lower than minimum conventional naphtha steam cracking. This outcome was expected given the prevalent use of fossil-fuel in the farming phase both for energy use and as fertiliser feedstock, in addition to enteric fermentation and LUC impacts.

Within the propane steam cracking pathways, eucalyptus stands out as the top-performing raw material. Its GHG footprint is just 0.8% below the upper threshold of the fossil fuel-based range. Conversely, the beef tallow pathway has the highest GHG emissions regardless of whether LUC emissions are considered. Specifically, with credits and excluding LUC emissions, GHG emissions surge to 373% above the upper level of the fossil range. Without considering credits, this value increases to 569%. The soybean routes, on the other hand, present a different scenario: if LUC emissions are excluded, their GHG emissions fall under a similar range as their fossil-based counterpart – only 9.5% above the fossil upper level. When accounting for LUC, even with carbon storage taken into account, the emissions double the fossil upper range.

On the naphtha steam cracking pathways, GHG emissions are



**Fig. 4.** Intercomparison of GHG emissions for all ethylene production pathways assessed. Median and error bars refer only to the carbon footprint without credits bars. The difference between probabilistic and deterministic values was not assessed for the no LUC cases (processed beef tallow and soybean oil).

slightly lower than those from propane cracking. Noteworthy, corn and wheat do not perform well in terms of GHG emissions, even when assuming carbon storage. Sugarcane ethanol (AtJ) performs relatively well – both the conventional and cellulosic routes – only falling behind the eucalyptus routes. When considering carbon storage, sugar beet could be a competitive raw material. However, sugarcane and eucalyptus still show better performance.

Closing the steam cracking alternatives, gasoil cracking routes perform better than those from naphtha and propane for all feedstocks, excluding eucalyptus. This directly relates to the high gasoil yield in the BtL route and the choice of 1 tonne of ethylene as the functional unit, given that gasoil steam cracking presents higher yields for heavier HVCs relative to propane and naphtha as feedstocks. Indeed, GHG emissions from the bio-based gasoil routes (either through conventional or cellulosic sugarcane) to bioethylene are significantly lower than those from fossil-based ethylene when carbon storage is considered. If carbon storage is considered, most feedstocks produce lower GHG emissions than those from the fossil ethylene range, except for the beef tallow and soybean routes.

Finally, the ethanol dehydration route, which is only assessed for sugar-related feedstocks, is the best-performing route for all ethanol-related feedstocks. The order of better raw material performance, from the lowest to the highest carbon footprint, is: sugarcane, sugar beet, corn (BR, then US), and wheat.

Overall, the sugar/starch crops show the best environmental performance in terms of GHG emissions, whereas oily crops present higher GHG footprints, especially when including LUC impacts of soybeans/beef tallow routes, a finding corroborated by the literature (Bos et al., 2016). When we do not account for carbon storage at the end-of-life phase, only the processes using sugarcane have GHG emissions similar to those from fossil-based ethylene. This comparison holds true specifically for gasoil steam cracking and ethanol dehydration.

The routes involving conventional sugarcane and beef tallow exhibit the highest accumulated uncertainty, as indicated by their larger error

bars. This is primarily attributed to the broad spectrum of farming practices observed across different regions and time frames of plantation in Brazil. The probabilistic results for the sugarcane routes are usually higher than the deterministic value. This suggests that our study employs reference technologies that align with the more productive and less energy-intensive cases.

Conversely, the deterministic values for the eucalyptus and corn routes tend to exceed the probabilistic ones. This indicates that the selected inventory parameters could be somewhat pessimistic when compared to the parameterisation of the sugarcane routes.

Routes involving cellulosic sugarcane ethanol, soybean, and wheat display deterministic values that are close to the probabilistic ones. This suggests that the values used in the inventory are likely close to the median values found in the literature, making this a realistic approach.

### 3.2.2. Steam cracking x ethanol dehydration

Bioethanol dehydration performs better than steam cracking routes. This is easily explained considering that ethanol dehydration does not require any processing of intermediate products (see Table 1) - the ethanol obtained in the intermediate production phase can be directly dehydrated into ethylene. Steam cracking, on the other hand, is fed with hydrocarbons from energy-intensive HEFA, BtL, and AtJ feedstock production routes. However, while steam cracking also co-produces propylene, butadiene, and aromatics, ethanol dehydration is an on-purpose route, i.e., dedicated to a single product. Although allocative methods were used to handle coproduction, it is noteworthy that alternative routes such as biopropane dehydrogenation or biomethanol-to-olefins – thus, also their emissions – would be needed to deliver the same basket of products.

### 3.2.3. Regional comparison

In this study, we evaluated the GHG footprint of bioethylene in Europe, the US, and Brazil. In Europe, only sugar beet and wheat were evaluated as raw materials. The best-performing option in Europe is bio-

ethanol dehydration using sugar beet as raw material. Routes based on wheat at least double the GHG emissions compared to those based on sugar beet. In the US, where corn was the only raw material evaluated, the gasoil steam cracking and the bio-ethanol dehydration pathways show similar performance, with slightly better results in the latter case. In Brazil, where several raw materials were evaluated, sugarcane-based routes perform better, with bio-ethanol dehydration being the best option.

In general, among the evaluated routes, there are respectively ten and fourteen options in Brazil with a carbon footprint lower than the best European and US alternatives. The worst performing routes were also found in Brazil: beef tallow with and without LUC show a range of results between 6.6 and 17.1 kg CO<sub>2</sub>e/kg ethylene (subject to route, LUC, and carbon storage considerations), mostly due to high enteric fermentation methane emissions in the cattle production phase.

#### 4. Discussion

Among all pathways analysed in this work, ethylene production in Brazil through sugarcane bio-ethanol dehydration presents lower GHG emissions than all steam cracking routes in any of the regions assessed in a cradle-to-gate perspective, as presented in Section 3.2. On the contrary, beef tallow routes considering LUC present the highest emissions, with low variation between propane, naphtha, or gasoil steam cracking routes. Routes based on beef tallow (with or without LUC) and soybean oil (with LUC) show considerably higher emissions than all the alternatives assessed.

This study corroborates the findings of prior studies on environmental assessments of biofuels and biomaterials, which have noted that: (i) bioplastics GHG emissions can be higher than their fossil-based counterparts depending on land-use emissions, process energy use, and end-of-life strategies (Liptow and Tillman, 2012); (ii) emissions from similar bioenergy- or materials-systems may differ subject to the type of raw materials, technologies and system boundaries as well as site-specific parameters (Cherubini et al., 2009); (iii) assumptions over biogenic carbon storage in biomaterials are critical to conclusions on fossil-versus bio-based materials (Pawelzik et al., 2013).

However, conclusions on scaling-up low-carbon production of bio-ethylene require further discussion. Specificities concerning biomass use for plastics production deserve attention, namely: (i) the use of energy for non-combustion purposes and the climate implications of final disposal alternatives; (ii) the land-use, energy, food, and material nexus; and (iii) economies of scope and scale as well as material-energy synergies in biorefineries. These topics are more thoroughly discussed below.

##### 4.1. Plastics use and final disposal

This work assessed the cradle-to-gate carbon footprint of bio-ethylene. The remainder gate-to-grave emissions are comprised by downstream processes (such as polymerisation and moulding), use and final disposal phases. In the former, the scale and quality of the energy demand are equally relevant for both fossil fuel and bio-based ethylene, and previous studies indicate a much less relevant role in cradle-to-grave emissions (Liptow and Tillman, 2012). On the other hand, the latter two deserve further discussion when considering the use of biomass for non-energy purposes. To be able to fairly compare fossil and bio-based ethylene, we considered two scenarios: one which the carbon fixed during photosynthesis is reemitted and one that is permanently stored.

In drop-in bioethylene, the carbons of each molecule are part of the biogenic carbon cycle. In contrast, the fossil carbons in conventional petrochemicals originate from the geological carbon cycle. The main issue concerning the use and final disposal phases is when, or if, the carbon stored in the molecule will be released as CO<sub>2</sub> to the atmosphere, which directly derives from the material service it delivers (i.e. applications and age-cohorts), as well as its final disposal after its lifetime. If

the carbon is never released back into the carbon cycle – an idealistic scenario of “permanent storage” – the amount of CO<sub>2</sub> in the ethylene molecule must be subtracted from the total process footprint, assuming *carbon storage*. However, if the carbon is released, the emitted amount is offset by the fixation during photosynthesis, and no additional subtraction is needed for the footprint assessment.

Bioethylene and its derivatives production could be considered carbon negative provided that downstream emissions (gate-to-grave) are not higher than its cradle-to-gate GHG emissions. Although properties of drop-in plastics such as bio-inertness and corrosion resistance lead to plastic durability, the assumption that bioplastics ending up in landfills or long-term applications store biogenic carbon and thus deliver negative emissions is not straightforward. Methane emissions by photo-degradation have been reported in landfills, for example (Royer et al., 2018). Concerns also exist over other environmental issues related to landfilling, such as soil pollution by microplastics impacting the soil biota (Sajjad et al., 2022). Likewise, it is not safe to say *a priori* that bio-based plastics used in buildings will be applied in long-lasting infrastructure and eventually will have their lifetime extended through reuse, refurbishment, or remanufacture measures (Mitchell-Larson et al., 2022).

However, encouraging the use of drop-in non-degradable bioplastics in long-lasting green infrastructure (e.g. roads surfaces, municipal sewage and water piping, roofing) through carbon accreditation while restricting landfill and incineration could help slow and close the plastic loops, respectively (Camilla C.N. de Oliveira et al., 2021; Karan et al., 2019). As Stegmann et al. (2022) show, plastics could become a net negative sector by reducing consumption of feedstock and storing biogenic carbon in bio-plastics in the long term if a circular bioeconomy – meaning promoting increased biomass use as feedstock and recycling – is implemented (Stegmann et al., 2022).

Methods of carbon removal certification have been recently developed by the European Commission, which includes “carbon storage in products” as a category, referring to activities “that store atmospheric and biogenic carbon in long-lasting products or materials (European Commission, 2022). Nonetheless, to be considered as a valid CDR option, the proposal must further define the meaning of “long-lasting”, ensuring that the renewable biogenic CO<sub>2</sub> captured in products is kept out of the atmosphere permanently and bringing other environmental benefits related to plastic pollution reduction.

These environmental benefits could also be coupled with the provision of essential material services delivery. Whereas all assessed regions will need to increase infrastructure for the energy transition (i.e. light composites for wind blades, electrical insulation materials, solar PV module components, and connections), Brazil is the only one that lacks basic sewage and water management networks. In 2020, around 45% of the Brazilian population did not have access to sewage treatment, and 15% to water provision networks (SNIS, 2021). Displacing fossil to bio-based polymer use and from short-to long-lived applications would not only provide climate change mitigation benefits but would also improve resource efficiency and collective access to decent living standards (Rao and Min, 2018).

Therefore, policy strategy should aim at coupling climate change and plastics marine pollution mitigation with essential services delivery by certifying drop-in bioplastics production and use that transition away from the current paradigm and aim at narrowing, and slowing plastics loops by reducing, reusing (or extending lifetimes) and recycling plastics, respectively (Bucknall, 2020; UNEP, 2023). To this end, policy-making should aim to 1) ban the use of ethylene in non-essential packaging and single-use applications, while increasing its use in applications that benefit from the corrosion and mechanical resistance properties of ethylene-derived materials (i.e., long-lived applications), 2) ensure an increased lifetime of bio-based drop-in polymers that may benefit from carbon credits and appropriate and safe disposal when it is discarded after decades of use (e.g. repurposing to foundations or roads and preventing bio/photodegradation), 3) encourage the substitution of



non-degradable fossil polymers for degradable bio-based ones in essential single-use applications such as personal protective equipment, and 4) promote the use of renewable electricity for low- and medium-temperature heat requirements in downstream processes. Thus, as part of a broad circular bioeconomy strategy towards the cascading and efficient use of biomass and wastes, integrated biorefineries contribute both to increasing the total value of biomass by producing lower- and higher-value products – i.e., fuels and olefins – and to reducing GHG emissions of energy and materials service provision by substituting fossil-based fuels and materials (Cheng et al., 2020; Stegmann et al., 2020).

#### 4.2. Land-energy-material-food nexus

IEA's estimates indicate that the passenger vehicle fleet will shift toward battery-electric and fuel-cell-electric mobility in the coming decade (IEA, 2021). This would lead to ethanol production overcapacity in all countries/regions investigated, meaning an opportunity for brownfield redevelopment/repurposing strategies. In 2019, the US produced 1.26 EJ of ethanol, followed by Brazil and Europe with 0.68 EJ and 0.12 EJ, respectively (RFA, 2022). Considering a scenario of full electrification<sup>2</sup> of the passenger vehicle fleet, the total equivalent ethylene production would be ca. 45 Mt, if ethanol production capacity would be used for material rather than energy purposes. This represents around a quarter of the current ethylene demand globally without any further LUC implications (OGJ, 2015). Although green ethylene does not compete with fossil ethylene on pricing today, the strengthening of climate policy could render revenues from carbon credits and increase its competitiveness (Oliveira et al., 2020). Moreover, scaling up and further technological learning could improve environmental and economic performance, closing the gap between best-performing bio-based routes and the conventional fossil ones.

In this sense, an LCA analysis alone might not be the best tool to dynamically analyse land-use impact associated with biomaterials. From an integrated assessment perspective, Oliveira et al. (2021) indicate that ethanol production in Brazil could be repurposed to ethylene to make up for market loss due to mobility electrification (Oliveira et al., 2021).

Furthermore, restoring degraded land could have a role in increasing the agricultural yield and reducing the pressure on native forest. Around 177 Mha of agricultural land were affected by human-induced degradation in Northern America in 2015, and 56 Mha in Western and Central Europe (FAO, 2021b). In Brazil, around 90 Mha of degraded land were degraded pastureland in 2020, of which 25 Mha were severely damaged (LAPIG, 2022). For comparison, the total land use for sugarcane production in Brazil in the 2021/22 harvest was around 8.3 Mha (CONAB, 2022). Enhancing the implementation of integrated crop-livestock-forestry systems can be used as a strategy to rehabilitate degraded land productivity without expanding the agricultural frontier while meeting demands for food and improving social and economic indicators (Costa et al., 2018).

This suggests that the sustainability of bioethylene pathways is closely associated with a zero-deforestation strategy and the adoption of conservation practices to native forestry ecosystems. If policymaking is not strong enough to prevent native biomes deforestation and food insecurity, the use of bio-based feedstocks for non-energy purposes may inflict or exacerbate direct and indirect land-use change, also increasing the decarbonisation burden to other sectors (Fiorini et al., 2023; Rochedo et al., 2018).

#### 4.3. Materials-energy synergies in biorefineries

Among the evaluated pathways, in general, bio-ethanol dehydration

routes lead to less GHG emissions. This option also benefits from other advantages, such as the production of ethanol being a mature technology (IEA, 2022a). Also, in bio-ethanol production, the sugar fermentation stage releases a pure stream of CO<sub>2</sub>, meaning that its capture does not incur in high energy penalties (Restrepo-Valencia and Walter, 2019). Thus, ethylene production from ethanol dehydration routes might benefit from bioenergy with carbon capture and storage (BECCS), improving its carbon footprint performance (C.C.N. de Oliveira et al., 2021).

Nevertheless, ethanol dehydration is an on-purpose route, i.e., it is dedicated to synthesising one product – bioethylene – whereas steam cracking is a multi-product route that converts hydrocarbons to ethylene but also propylene, butadiene, aromatics, and energy backflows. Thus, while the choice for ethanol dehydration routes may lead to less GHG emissions, it is important to consider that steam cracking routes might become preferable due to the synthesis of other valuable products.

Furthermore, the bio-derived hydrocarbons that are employed as feedstocks in the steam cracking route are themselves also synthesised through multi-product routes, in biorefineries where energy and materials feedstock (e.g. bio-naphtha) are co-produced on the same platform. Thus, once again, there is a multitude of valuable by-products, such as bio-propylene, aromatics, aviation kerosene or green diesel, which are premium products usually associated with high revenue margins.

Besides these economies of scope associated with the steam-cracking routes, additional advantages exist in the production of the required hydrocarbons in biorefineries. For example, ramping up the sustainable production of advanced biofuels is considered a key solution to smoothen the transition towards a low-carbon energy system due to: 1) the difficulties to electrify modes such as aviation and international shipping, 2) the synergies with the established fossil fuel-based infrastructure (drop-in biofuels can take advantage of existing engines and structure), 3) the potential to achieve negative emissions (i.e., bioenergy with carbon capture and storage, (BECCS) particularly in the FT-BtL and AtJ routes) (Daiglou et al., 2019; Müller-Casseres et al., 2022; Rogelj et al., 2018).

In the aviation industry, specifically, some pathways which produce drop-in bio-based jet fuel are already approved for blending with fossil jet fuel (IATA, 2019), in line with the sectors' decarbonisation strategy (Carvalho et al. 2019; Fiorini et al., 2023; IATA, 2021). These technological options include routes evaluated in the present study, such as FT-BtL, HEFA and AtJ, which represent an opportunity for contributing to the decarbonisation of both the aviation and the petrochemical sectors.

Although bioethylene from steam cracking routes presents higher GHG emissions than ethanol dehydration-derived ethylene, the steam cracking routes may be more attractive if the value of the whole basket of products is considered. The evaluation of the multitude of configurations in a complex biorefinery and economic performance should be further detailed in future work as well as the environmental performance of on-purpose routes potentially required if sugarcane ethylene supply prevails. Though this is not in the scope of this study, an integrated assessment of energy consumption, GHG emissions reduction targets, materials demand, and land-use impacts in the regions analysed would be suitable to address this issue.

Furthermore, the use of bio-based feedstocks for energy, materials, and chemicals can play a role in shaping regional and municipal infrastructure planning decisions. Although our research primarily addresses the large-scale production of bioethylene in countries and regions with competitive biomass resources, encouraging local businesses to utilize organic waste can enhance value retention throughout supply chains and optimize resource utilisation (Portugal-Pereira and Lee, 2016; Yaashikaa et al., 2020). Multifunctional technological solutions have been identified as potential means to upgrade waste to high-value products while minimizing emissions (Malinauskaite et al., 2017). Consequently, decision-making should reflect the intricacies of these real-world realities.

<sup>2</sup> Excluding potential use of ethanol in ethanol fuel cells and hydrogen fuel cells powered with hydrogen based on ethanol steam reforming.

It is also worth mentioning that there is an opportunity for fossil-based naphtha use in ethylene production, even in climate mitigation scenarios. In conventional fossil fuel-based systems, the naphtha stream of oil refineries is primarily converted to gasoline and used as engine fuel in light vehicles. In 2019, 47 EJ of naphtha were produced for that purpose whereas 11 EJ were converted to plastics, synthetic fibres, and other chemicals (IEA, 2022b). However, as the transport sector decarbonises and electrifies, gasoline demand will probably decrease, increasing the availability of fossil naphtha as a chemical feedstock. Compared to its traditional use as fuel, diverting the naphtha stream for non-energy purposes combines value-added benefits with reduced emissions (de Oliveira et al., 2021; Oliveira et al., 2021; Tsiropoulos et al., 2015b).

As shown in Fig. 4, bio-based ethylene routes do not lead to lower emissions than fossil-based ethylene production if it does not account carbon storage. Therefore, fossil-based ethylene will probably continue to have a role in the short-to medium-term, even in climate-ambitious scenarios, especially when produced from light feedstock (i.e. ethane). This might be particularly relevant to natural gas-rich regions that benefit from high ethane availability, such as the US and the Middle East.

In the long term, the drop-in replacement logic might become obsolete given the high-weight oxygen in bio-based feedstocks. Carbohydrates, which contain more heteroatomic oxygens than conventional fossil hydrocarbons, might become more economically feasible if converted to oxygenated/oxidised materials (e.g. high-performance polyesters and polycarbonates), avoiding energy-intensive processing stages and leveraging from new functionalities (Cywar and Beckham, 2022; Fitzgerald and Bailey, 2017; Narala et al., 2022; Rosenboom et al., 2022).

#### 4.4. Limitations and future work

This work performed an attributional life cycle assessment of bioethylene production. To better understand the influence of methodological assumptions and background premises in the overall LCA impact results, an expanded analysis following a consequential approach may be conducted, which accounts for direct and indirect effects considering that the evaluated processes are part of a larger system (Kolosz et al., 2020). Also, using an economical allocation instead of physical could lead to different insights, particularly in the multi-products routes.

Moreover, while the primary emphasis of the study focussed on GHG emissions, exploring other impact dimensions is critical to discern potential impact trade-offs. As we scale up biomass production to mitigate GHG emissions related to fossil fuels use, other potential implications arise. These include increased water consumption, potential eutrophication from fertiliser use, acidification of water bodies and vegetation from ammonia and sulphur oxides emissions, biodiversity loss and concerns regarding human toxicity and ecotoxicity from the application of pesticides and herbicides (Weiss et al., 2012). All these dimensions warrant further investigation.

Furthermore, HEFA, FT-BtL and AtJ processes are designed to yield products in the desired range with limited flexibility. The parameters considered for these processes were aiming at the synthesis of jet fuel and/or diesel/gasoil as the main products to meet the demands of the aviation and maritime industries, which are hard-to-abate sectors (Sharmina et al., 2020), and also of freight transportation, which diesel use is predominant in countries such as Brazil (Prudêncio da Silva et al., 2010). Bio-based naphtha is, thus, a coproduct in all these processes. This premise would be aligned with the current practice, in which fossil naphtha is also a co-product of fuels production. Alternatively, higher yields of naphtha could be considered in case the biorefinery design strategy is more oriented to producing value-added chemicals than fuels (for example, by changing catalysts and operating conditions in the FT process).

Future work can also include further evaluation of the final disposal

strategies of bioplastics and the assessment of the circumstances under which bioplastics might serve as a permanent carbon dioxide removal strategy. Moreover, an analysis of the environmental performance of non-drop-in intermediates, i.e., chemicals that do not require the removal of oxygens from carbohydrates is also necessary. For short-to medium-term, the current pathways to ethylene appear as front runners to decarbonize the plastics industry. However, for long-term sustainability in polymer production, it is essential to explore innovative breakthrough methods. Both cases entail the evaluation of bio-polymers in terms of their functionality, instead of their composition.

Finally, we highlight the importance of reflecting upon the suitability of this methodology, designed for large-scale production of bioethylene, to other projects across different geographies. When formulating environmental policies, it's crucial to recognize and address local specificities. As such, the methodology should be adapted to fit local contexts, paving the way for more relevant future studies.

#### 5. Final remarks

The development of either greenfield or brownfield projects to supply bioethylene does not necessarily deliver lower emissions than conventional fossil ethylene. However, the shift from fossil to bio-based feedstocks for HVCs production represents a complete redefinition of supply-chains with multiple and complex outcomes, potentially delivering lower life cycle GHG emissions.

Firstly, it can pave the way for local and regional production, including the development of new technologies, as well as new logistics and distribution systems. This can reduce dependence on fossil fuels across various energy and material end-uses. While bio-based ethylene does not always outperform its fossil-based counterparts in environmental performance, it often matches them closely. An essential benefit of this feedstock substitution lies in reducing the dependency on fossil fuels as feedstocks, indirectly leading to decrease of emissions through the lower utilisation factor of the petroleum refining sector.

Secondly, this shift represents not only a way to decrease emissions of a hard-to-abate sector, but to position it at the forefront of mitigation, altering the degree of climate action expected from such a sector. Using biomass for plastic production has opportunities to capture atmospheric CO<sub>2</sub> throughout all the supply chain – from BECCS to ultimately storing CO<sub>2</sub> in durable materials. Lastly, this transition offers a platform to impact policymaking regarding single-use consumption patterns, given that negative emissions are only achieved if biogenic CO<sub>2</sub> is stored in a long-lived application.

However, bio-based plastics sustainability hinges on low-carbon agriculture and their use and end-of-life strategies. Sustainable farming and land use practices are key to ensure bioethylene low-carbon production. Equally vital are circular economy measures to narrow and close the loop during the product's lifespan. It is important to highlight, however, that permanent and durable storage of carbon dioxide by non-geological removal strategies – such as storage in bio-based products – cannot be guaranteed. As carbon removal in materials sparks intense debates, the study underscores the imperative of harmoniously designed climate mitigation and circular economy policies to bolster resource efficiency and curtail GHG emissions cohesively. In forging ahead, future studies could delve into nuanced carbon storage mechanisms and their dynamic interplay with bio-based materials.

#### CRediT authorship contribution statement

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Writing – review & editing. **Lucas Carvalho:** Conceptualization, Methodology, Data curation, Investigation, Writing – original draft. **Gerd Angelkorte:** Conceptualization, Supervision. **Ana Carolina Oliveira Fiorini:** Conceptualization, Supervision, Writing – review & editing. **Pedro Rua Rodriguez Rochedo:** Conceptualization, Supervision. **Joana Portugal-Pereira:** Conceptualization, Supervision, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – review & editing. **Alexandre Szklo:** Conceptualization, Supervision, Writing – review & editing. **Roberto Schaeffer:** Conceptualization, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.139376>.

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