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# Techno-economic, life cycle, and environmental cost assessment of biojet fuel obtained from *Pinus pinaster* by turpentine hydrogenation†

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The reduction of greenhouse gas (GHG) emissions caused by the aviation industry is a complex challenge. Biojet fuels can significantly contribute to lowering the GHG emissions, but their cost is still a major issue. In this study, life cycle assessment (LCA) and environmental cost assessment were used to evaluate the production of biojet fuel obtained from *Pinus pinaster* resin in Spain through hydrogenation of turpentine. Both studies were carried out using the software SimaPro. The Product Environmental Footprint (PEF) method was employed to quantify the environmental impacts. A process simulation scheme with Aspen Plus was carried out to evaluate the feasibility of an industrial implementation and to assess mass and energy balances for being used in the LCA. Production and external costs due to environmental impacts obtained by the Environmental Prices methodology have been considered. The results show that emissions are 5.9 g $CO_2$ eq. per MJ, when a yield of 4 kg of resin per tree per year is considered, which means a reduction of 93% compared to the fossil jet fuel (stated in Directive (EU) 2018/2001 as being of 94 g $CO_2$ eq. per MJ). In addition, if the resin yield increases above 6 kg per tree per year or/and if environmental externalities are considered, biofuel becomes cost-competitive compared to fossil jet fuel. In conclusion, this research shows that the biofuel obtained from pine resin hydrogenation is cost-competitive and can be blended with traditional jet fuel to reduce the environmental impact of the GHG emissions from the aviation industry.

## 1. Introduction

Greenhouse gas (GHG) emissions from aviation activities have increased due to the considerable growth of air traffic in recent years.[1,2] Anthropogenic carbon dioxide ($CO_2$) causes more than three quarters of total GHG emissions.[3] Aviation $CO_2$ eq. emissions nearly doubled from 88 to 156 Mt $y^{-1}$ between 1990 and 2005 and increased by almost 5% between 2005 and 2014.[4] Nowadays, aviation $CO_2$ emissions currently represent between 1.7% and 2.3% of the global $CO_2$ emissions,[5] while European aviation accounts for 22% of world aviation $CO_2$ emissions.[6] Furthermore, international aviation $CO_2$ emissions are estimated to almost quadruple by 2050 compared to 2010.[7]

As in other sectors, the aviation industry also seeks to mitigate its environmental impact. In 2017, the International Air Transport Association (IATA) focused on ensuring greater voluntary participation of countries and preparations for the implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The four main objectives on which the aviation industry focuses are: (1) carbon neutral growth from 2020; (2) 50% reduction in carbon emissions from 2005 to 2050; (3) improved fuel efficiency by 1.5% on average from 2020 (by improvements in turbines or by the use of lighter materials); and (4) reduced dependence on fossil fuels. The development of sustainable aviation fuels plays a main role in fulfilling these objectives.[8–12]

Today, aviation depends on Jet A-1 kerosene (produced from crude oil), but several options to produce biojet fuel are under investigation.[13] The European Advanced Biofuels Flight Path initiative was established as a road map to achieve an annual production of 2 Mt of biofuel for aviation by 2020.[6] The main limitations of biofuels are not technical, since several technologies are prepared for commercial deployment, but economic, political and market-related issues.[7,13] However, the aviation industry is increasing its efforts to encourage the development of aviation biofuels.[14]

In the last decade, over 165 000 flights have used a blend of sustainable aviation fuels (SAFs), and by the end of 2018, more than 40 airlines had used SAF.[14,15] SAFs are a very attractive

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option because they do not require modifications in aircraft engines (so-called "drop-in" biofuels) and can be easily blended with fossil jet fuel. Different feedstocks have already been used to produce biojet fuel, such as babassu, coconut, jatropha, seaweed, camelina, and algae.[14,16–20] Thus, biofuels are increasingly being used to reduce the environmental impacts of aviation and to ensure energy security in the aviation industry.[21] The American Society for Testing and Materials (ASTM) standard D1655 defines the minimum property requirements for Jet A and Jet A-1.[22] The technical certification of SAF is regulated by ASTM D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons), which evaluates the technologies that can be used for producing a SAF within specifications.[23]

Market-based measures are necessary to meet the objectives of reducing aviation emissions, since technological and operational improvements alone are not sufficiently considered. Limiting the emission of certain GHG and marketing them have been proven to work. This system has contributed to reducing the carbon footprint of the aviation sector by more than 17 Mt per year.[24]

One of the challenges facing the production of biojet fuel is finding feedstocks that do not compete for land use (fertile land necessary for food production),[25–27] such as wastes, lignocellulosic materials or lipid materials from different species of algae. However, some of these options are in a state of development, not advanced enough for large-scale and commercially viable production. In the short and medium terms, the aviation industry is choosing vegetable oils, such as camelina or jatropha, and organic waste (such as used frying oil), because they are technically easier to use, can cause a high reduction of $CO_2$ emissions and are economically more viable than lignocellulose or algae.[28] Nevertheless, two important challenges for the implementation of biofuels remain unsolved: to guarantee sufficient production (considering multiple feedstocks) and to obtain a competitive price for the end user, since nowadays, the price is practically double that of traditional jet fuel.

In this context, pine oil turpentine, obtained from resin, has already been studied as a potential renewable fuel for diesel engines[29] and presents suitable physical and thermal properties.[30] Pine resin consists mainly of terpenes (10–15%), abietic acids (60–75%), and other compounds (5–10%). The lighter compounds (terpenes) are separated from the heaviest ones through a distillation process, resulting in turpentine and rosin.[29] Rosin is the largest fraction obtained from the process,[31] and it consists mostly of resin acids, including abietic, dehydroabietic and pimaric acids.[32] Turpentine, the lighter fraction, is composed of monoterpenes C10, mainly α-pinene and β-pinene with much minor amounts of D-limonene and myrcene. These compounds are all in the distillation range of fossil jet fuel and, potentially, can be used for the production of biojet fuel.[33,34]

Tree resin can be obtained from several pine species,[31] black pine (*Pinus pinaster*) being the most common in Spain and Portugal. In 2019, 316 kt of turpentine were produced worldwide, of which 125 kt were obtained from pine resin, 185 kt from the paper industry, and only 6 kt from stump wood. China is the largest producer of turpentine in the world (50%), followed by Brazil. Other producers are Indonesia, the United States, Portugal, Spain, Vietnam, Argentina, Mexico, and India.[35] In 2007, the highest world production of products derived from pine resin was reached, obtaining 170 kt of turpentine and 1050 kt of rosin.[36] The jet fuel consumption in the world was 11.979 kt in 2021;[37] thus, the hydrogenated turpentine could represent 2.64% of the world jet fuel consumption. In 2021, the resin production in Spain amounted to 30.0 kt, thanks to a government policy that supports the sector with the purpose of reforestation. If the resin production in Spain could return to the production levels of the 1960s, the gum turpentine distilled would be 11.0 kt, which added to the crude sulphate turpentine obtained from the paper industry (13.5 kt), could represent 0.35% of Jet A1 consumed in Spain in 2019 (6921 kt).

Thus, pine resin seems to be a very promising feedstock for biofuel production since: (1) it does not compete for fertile land necessary for food production; and (2) pine plantation is favoured because the management of forests and agricultural land is included in Spain as an activity in the Land Use, Land-Use Change and Forestry (LULUCF) to compensate GHG.[38]

The aim of this study is the techno-economic analysis, life cycle analysis (LCA), and environmental cost assessment of the production of biojet fuel obtained from *Pinus pinaster* resin in Spain.

## 2. Materials and methods

A life cycle assessment (LCA) of hydroturpentine of pine resin was performed to calculate the reduction in GHG emissions compared to fossil jet fuel (94 g $CO_2$ eq. per MJ) following the specifications of Directive (EU) 2018/2001.[39] The production of this biojet fuel from pine resin was simulated using Aspen Plus v.10.0, needed to (1) complete the inventory of the LCA and to (2) estimate fuel properties to determine if the biojet fuel complies with the ASTM D7566 standard. Finally, an environmental cost assessment was performed to assess the production cost of this biojet fuel (with and without environmental externalities) and to compare it to that of fossil jet fuel.

### 2.1. Life cycle assessment (LCA)

The Ecoinvent v.3 database was used as the main data source during the inventory stage.[40] The Product Environmental Footprint (PEF) method was used to quantify the environmental impact, as the European Union is promoting it to obtain uniformity in results from environmental studies.[41] The LCA values have been used with an attributional approach accounting for mass and energy flows along the fuel supply chain.[42] All data were analysed using the Sima Pro v.9.0 software.

The functional unit considered is the mass of biojet fuel necessary to produce 1 MJ in a turbine engine. The lower heating value (LHV) of this hydroturpentine biojet fuel is 43.1 MJ $kg^{-1}$ as it has been previously reported,[34,43] which means that 0.02320 kg of hydroturpentine are necessary to produce 1

MJ. The same figures are considered for fossil jet fuel (Jet A1) since an average LHV of 43.1 MJ kg$^{-1}$ has been considered.[44]

The life cycle inventory considers all the stages from the resin harvesting till the combustion of biojet fuel: (1) resin harvesting; (2) biojet fuel production; (3) biojet fuel combustion; and (4) transport. The system boundaries include the resin collection, the feedstock transportation, the jet fuel production and transportation, and the jet fuel combustion. The system boundaries and a legend identifying the raw materials, products, co-products, wastes, processes, and transport are shown in Fig. 1. Pine plantation, cultivation, and maintenance have not been included in the studied system. $CO_2$ emissions due to biofuel combustion have been considered nil, in accordance with Directive UE 2018/2001.[39]

**2.1.1 Resin harvesting or extraction.** *Pinus pinaster* has a great variation in resin production, from less than 1 kg per tree per year to average levels of 4–6 kg per tree per year. The best ones can frequently yield 10 kg per tree per year, with the highest recorded production being 30 kg per tree per year.[45] Therefore, 4 kg of resin per tree and year has been considered as the lower reasonable production value.

Environmental impacts in pine cultivation are not considered because the objective is either the reforestation or the production of biomass for the paper industry, but not for the production of tree resin. Moreover, resin oil is specifically considered as waste or residue from forestry and the forest-based industry by the EU Renewable Energy Directive II (RED II).[46] This directive also states that wastes and residues shall be considered to have zero life-cycle GHG emissions up to the process of collection of these materials. The main advantage of not considering the cultivation is in the impact category 'land use', which usually has the highest impact on biofuel LCAs compared to fossil fuel LCAs.[46] As resin harvesting is mainly a hand-made process, the environmental impacts of this stage are related with the resin transport from pines to the distillation factory (see Section 2.1.4). This study opens the door to use

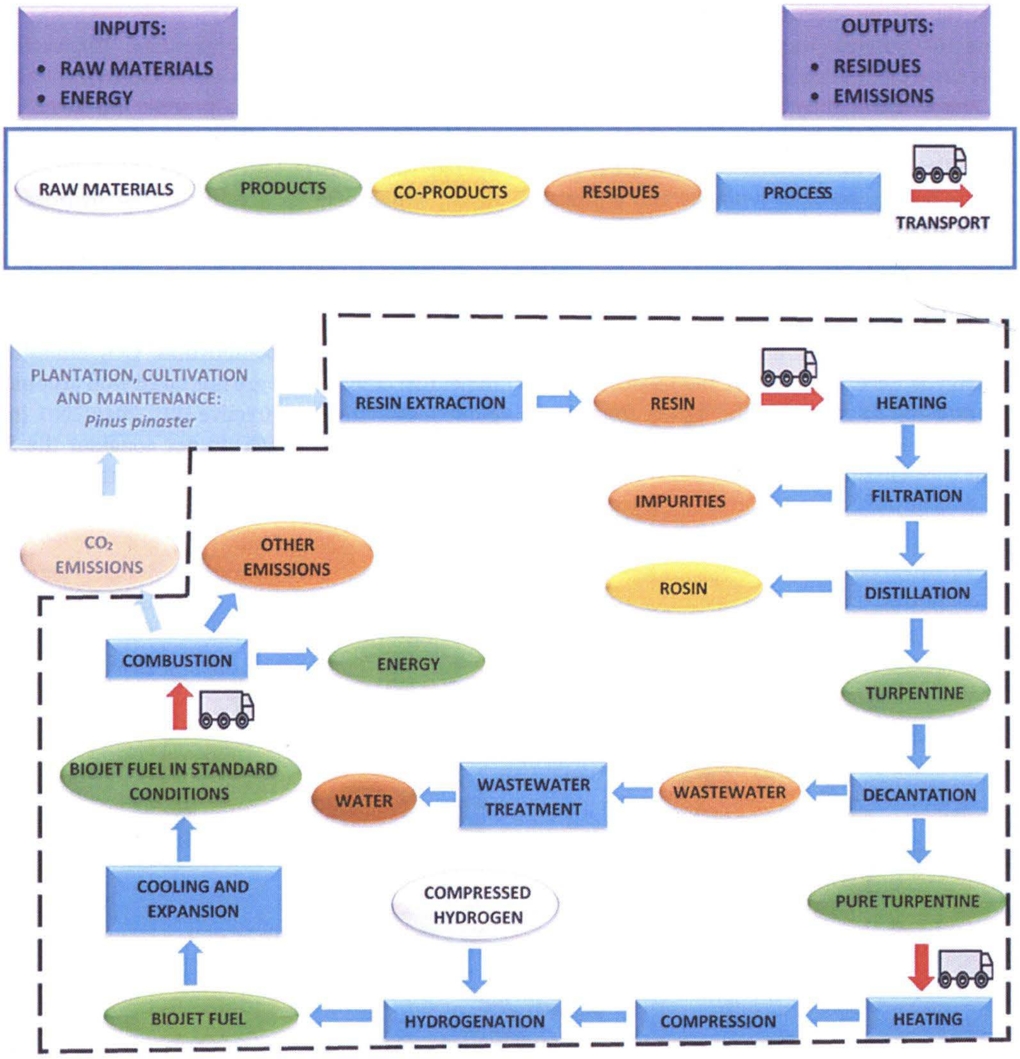

Fig. 1 Flowchart of the different stages considered in the life cycle of biojet fuel. The dashed line represents the system boundaries.

turpentine as feedstock for biojet fuel, which can be obtained directly from trees (resin) or from the paper industry (crude sulphate turpentine). This last input, not considered in this study, would increase significantly the potential total production of biojet fuel.

**2.1.2 Biojet fuel production.** The data used for biojet fuel production are based on a previous study.[34,47] The Aspen Plus simulation uses the Peng–Robinson thermodynamic model and consists of a distillation column (DIST) to separate the turpentine from the rosin, a hydrogenation reactor (HYD-REAC) to hydrogenate the turpentine, seven heat exchangers, and two compressors (see Fig. 2).

The biojet fuel production comprises eight stages (Fig. 2). All the data and processes used are detailed in ESI S1:†

*2.1.2.1 Resin preheating.* 1000 kg $h^{-1}$ of resin are heated from standard temperature to 450 K. Water vapour is produced in a natural gas boiler. The heat transfer efficiency for all the processes has been considered to be 90%.

*2.1.2.2 Resin filtering.* Resin impurities are removed prior to distillation. Only solid impurities such as splinters or pine spikes must be removed before distillation since they are considered wastes. No energy consumption has been considered for this process. Nevertheless, they could have an economic value in the market since pitch or tar could be obtained by their slow combustion. This would slightly benefit the environmental performance and the price of the biojet fuel.

*2.1.2.3 Resin distillation.* The reference temperature is set to 453 K, just above the boiling point of $\alpha$-pinene and $\beta$-pinene, main components of turpentine. Turpentine is obtained at the distillation head and rosin at bottom of the column. Wastewater is generated in the process and must be treated. Allocation of environmental impacts is based on mass, since rosin is considered as a coproduct because it has an economic value. A contribution of energy is necessary to heat the mixture to the operating temperature and to condense the lighter fraction of the distillation. The EER (Energy Efficiency Ratio) in the refrigeration circuit is considered to be 3.5.

*2.1.2.4 Turpentine decantation.* Turpentine is not soluble in water, so water can be removed by decantation. First, turpentine is cooled to a few degrees below its boiling point. Then, turpentine is extracted from the mixture as a liquid while the water continues in the gaseous state. Once this process is finished, the excess water from the process is cooled, so that it can be sent to wastewater treatment. In both processes, the energy that is needed is cooling energy.

*2.1.2.5 Compression and preheating of purified turpentine.* 11 atm (1.1 MPa) and 473 K are the conditions for an optimized hydrogenation of turpentine.[47] Isentropic compression and preheating is needed since it is extracted from the decanter at 423 K and 1 atm (0.1 MPa).

*2.1.2.6 Compressed hydrogen conditioning.* Hydrogen feed is assumed under high pressure conditions (200–400 atm, 20–40 MPa). To meet the same pressure and temperature conditions as those of turpentine, it undergoes an isentropic expansion and an increase in temperature. The compressed hydrogen production process was not included in the database and needed to be simulated using modified data of an existing Ecoinvent process (hydrogen, liquid {RoW}|market for|APOS, U).

*2.1.2.7 Turpentine hydrogenation.* Turpentine needs to be hydrogenated to meet standards established by ASTM D7566 for use as aviation fuel.[39] This process has been simulated using a stoichiometric reactor (RStoic) in Aspen Plus. The reactor was operated at 11 atm (1.1 MPa) and 473 K in the presence of 1% Pt/$Al_2O_3$, which acts as a catalyst. The hydrogenation reaction conversion is 95%.

*2.1.2.8 Biojet fuel conditioning.* Biojet fuel undergoes a drop in temperature prior to its final transportation at 1 atm (0.1 MPa) and 298 K.

**2.1.3 Biojet fuel combustion.** $CO_2$ emissions due to the biojet fuel combustion are not taken into account following the guidelines stated by Directive (EU) 2018/2001 (ref. 39) and the PEF methodology, which do not consider the fixation of $CO_2$ from the atmosphere. The rest of the emissions produced during the combustion of biojet fuel, except $SO_2$, are supposed

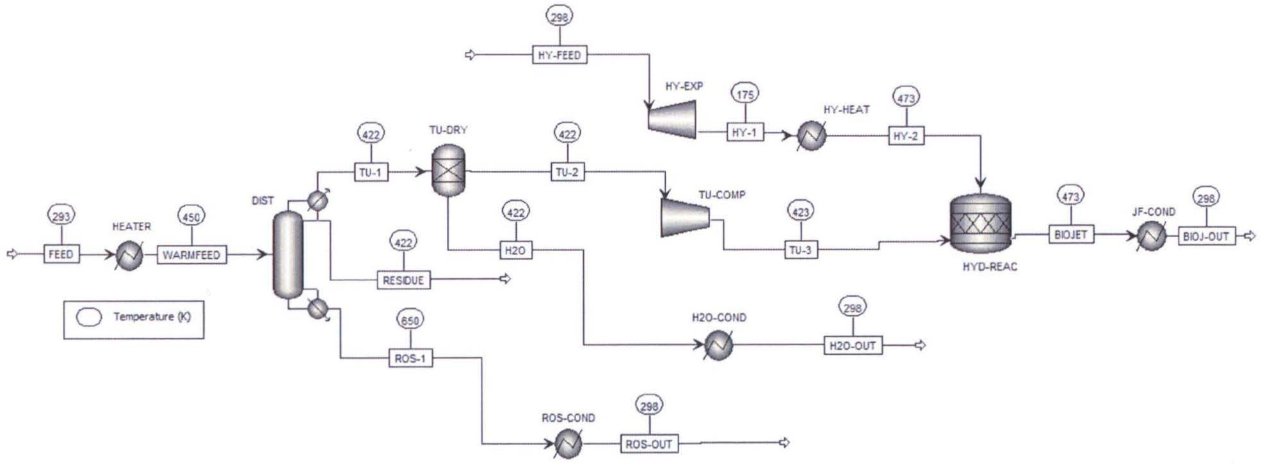

Fig. 2 Process flow diagram of Aspen Plus simulation for the production of biojet fuel from pine resin.

to be the same as those in fossil jet fuel combustion. Emission inventory is adapted from data collected in a Boeing 737–400 by the European Environmental Agency[48] and are shown in Table S1.10.†

**2.1.4 Transport.** Three ways of transport have been considered:

*2.1.4.1 Resin transport from the pine forest to the distillation factory.* Castilla y León and Castilla-La Mancha were the locations chosen for this project since they account for 41% of *Pinus pinaster* pine forests, and they are the highest resin production regions in Spain. The forests with largest areas were chosen, and the number of pine forests selected from each province was linked to their resin production. The locations of the pine forests are represented by a tree in Fig. S2.1.† There are only seven distillation factories in Spain, represented with a circle in Fig. S2.1.† The average distance from a factory to a pine forest has been estimated from all the distances between factories and the selected pine forests (see ESI S2†). An average of 142.2 km has been calculated.

*2.1.4.2 Turpentine transport from the distillation factory to the biorefinery.* Six biorefineries are chosen with potential to produce biojet fuel, including the hydrogenation process[49] (represented by squares in Fig. S2.1†). The average distance between distillation factories and biorefineries has been estimated to be 503.7 km (see ESI S2†).

*2.1.4.3 Biojet fuel from biorefinery to the consumer.* Pipeline transport statistics have been used to find out the average traffic by pipeline (80.30%), road (8.50%), and ship (11.20%) for the transport of petroleum products.[50] The same transport has been considered for biojet fuel.

### 2.2. Environmental and production cost assessment

The life cycle cost analysis (LCCA) collects all the costs associated with the life cycle of a product taking into account all the stakeholders involved (*i.e.*, suppliers, producers, users, and personnel involved in the management of the product end of life). However, depending on the type of LCCA, the included costs can vary.[51] In this study, the cost of the biojet fuel takes into account not only actual production costs, but also external costs due to environmental impacts calculated by the "Environmental Prices" methodology developed by CE Delft.[52,53] Critical points that influence the product cost are identified and improved to make this biojet fuel competitive compared to the fossil fuel Jet A1. Furthermore, a new methodology named "Environmental LCCA" has been developed taking into account not only the costs associated with environmental impacts (based on the "Environmental Prices" methodology[54]), but also the costs associated with personnel, raw materials, operation, transport, and other costs (see Table 2).

The functional unit used for the environmental cost assessment is one kilogram of biojet fuel burnt in a turbine of a commercial airplane (instead of 1 MJ that was used for LCA). The system includes the same stages that are analysed in the LCA (see Fig. 1). The investment costs of the project and the necessary machinery are not considered. The economic inventory, which is a compilation of all the unit costs that influence the final cost of biojet fuel, is divided into four parts: the first two correspond to the production processes, and the other two correspond to transportation and externalities.

**2.2.1 Resin production.** Cost of resin production depends on labour costs, productivity of the resin tree and forest exploitation auction costs. Thus, a resin worker has an hourly wage of 8.08 € per h, based on the "Collective Agreement for the Forest Activities Sector of the Community of Castilla y León 2016–2019", which considers these workers as "specialized operating personnel".[54] According to Blanco,[55] a resin worker needs 0.088 working hours per pine. Considering a production of 4 kg per tree per year, the wage of the resin workers can be expressed as 0.178 € per kilogram of extracted resin. As the pine workers have a fixed wage, this value depends on the amount of resin extracted.

The forest exploitation auction cost is associated with the "leasing" of a tree over a period of time, and it may vary depending on the owner and the place, ranging from 0.2–0.6 € per tree per year. Thus, a cost of 0.45 € per tree per year is considered, which is the price offered by the Municipality of Cuéllar (town in Castilla y León). The forest exploitation auction cost is expressed as 0.113 € per kilogram or resin, since the output of resin harvesting is mass (kg) of resin harvested.

**2.2.2 Biojet fuel production.** Biojet fuel production considers all the processes from the distillation of resin to biojet fuel conditioning (see Fig. 2). Fixed costs are estimated using the Aspen Economic Analyzer. For a production of 8528.57 t of resin per year,[56] fixed costs are 1 080 418.5 € per year. The unit cost for personnel and maintenance is 0.1267 € per kilogram of resin. Operating costs consider electricity, natural gas, and hydrogen. Cost of electricity for industrial use is 0.092 € per kW per h;[57] cost of natural gas for non-domestic use is 0.0326 € per kW per h;[58] and cost of compressed hydrogen is 1.34 € per kg, according to a personal communication from ZECSA company.

**2.2.3 Transport.** A rigid three-axle vehicle with a payload of 16 t has been selected for the transport from the pine forests to the distillation factory, the cost of transport being 1.2118 € per km.[59] As the unit of measurement for transport in SimaPro is t km, the cost per kilometer was divided by the payload, obtaining a price of 0.0757 € per (t km). As the transportation from the biorefinery to the point of consumption was considered to be the same as for fossil fuels, transportation by road, pipeline, and cabotage has been considered. An articulated tanker of dangerous goods with a payload of 20 t was chosen for transportation from the biorefinery to the point of consumption, the cost of this vehicle in payload being 1.8833 € per km or 0.0942 € per (t km). The prices for transportation by pipeline (0.0359 € per (t km)) and cabotage (0.0353 € per (t km)) have been obtained from the CLH webpage, considering the density of biojet fuel.[60]

All the unitary costs of the processes are summarized in Table 1.

**2.2.4 Environmental externalities.** The Environmental Prices v.1 methodology[61] is used to assign the cost to each category of environmental impact. Environmental Prices are indices that calculate the social marginal value of preventing

Table 1 Unitary costs of the processes considered in the economic analysis

| | | |
|---|---|---|
| Personnel costs | Resin collector wage | 0.1777 € per kg |
| | Plant worker wage | 0.1267 € per kg |
| Operation costs | Hydrogen cost | 4.87 € per kg |
| | Electricity cost | 0.083 € per kW per h |
| | Natural gas cost | 0.0326 € per kW per h |
| Transport costs | Three-axed vehicle | 0.0757 € per t per km |
| | Articulated tanker | 0.0942 € per t per km |
| | Pipeline | 0.0359 € per t per km |
| | Cabotage | 0.0353 € per t per km |
| Raw materials | Fossil jet fuel | 0.394 € per kg |
| Other costs | Forest exploitation auction costs | 0.1125 € per kg |

emissions, expressing it in euros per kilogram of pollutant.[62] These costs, called external costs or externalities, allow giving a numerical price on the value that society attaches to environmental quality. Since for biofuels, $CO_2$ emissions during combustion are not considered, taking into account these environmental externalities reduces their cost to be close to that of a fossil fuel.

A payload *versus* range analysis, which considers the distance that an airplane can fly with the same payload (passengers and cargo), has also been made for the biofuel and compared to Jet A-1.[60] This study has been included in ESI S3.†

Table 2 Composition (in mass fraction) of the outlet liquid streams from the distillation column (DIST) and the hydrogenation reactor (HYD-REAC) in the flow diagram in Fig. 2

| Monoterpenes | Turpentine (TU-2) | Hydrogenated turpentine (biojet) |
|---|---|---|
| α-Pinene | 0.673 | 0.020 |
| β-Pinene | 0.215 | 0.005 |
| Myrcene | 0.010 | 0.001 |
| Limonene | 0.027 | 0.000 |
| *Cis*-pinane | 0.000 | 0.764 |
| *Trans*-pinane | 0.000 | 0.189 |
| *Cis*-*p*-mentane | 0.000 | 0.003 |
| *Trans*-*p*-mentane | 0.000 | 0.006 |
| *p*-Mentane | 0.000 | 0.003 |
| 2,6-Dimethyloctane | 0.000 | 0.009 |
| Total | 1.000 | 1.000 |

# 3. Results and discussion

## 3.1. Process simulation

The overall process of vacuum distillation of natural resin and hydrogenation of turpentine simulated with Aspen Plus v.10 showed consistent simulation results. Table 2 shows the composition (in mass fraction) of turpentine from the distillation column (DIST) and the composition of turpentine after hydrogenation in the reactor (HYD-REAC), supposing that the hydrogenation conversion was 95%. This hydrogenation reaction has been proposed using platinum on alumina pellets as catalysts and mild hydrogenation conditions. As observed, the olefinic components after this hydrogenation have been greatly reduced.

Table 3 shows the main properties estimated with Aspen in the turpentine after distillation and the turpentine after hydrogenation. The values for Jet A1 were measured in a Jet A1 sample obtained from the Spanish company Exolum (formerly CLH) and reported in a previous paper.[34] The values required in ASTM D7566 (ref. 63) for Jet A-1 are also included in brackets. The hydrogenated turpentine fulfills all the specifications required for Jet A1. However, Aspen overestimates the LHV values (around 44 MJ $kg^{-1}$) when the experimental values are close to 43 MJ $kg^{-1}$.[34]

The process simulation converges smoothly, and the mass and energy balances and the preliminary equipment design predict the industrial feasibility of the whole process (see Tables 4 and 5). The net energy revenue of the process is high (5559.9 MJ $h^{-1}$). The atom economy (the amount obtained of the desired product divided by the amount of feedstock used[64]) is low (0.129) since only 129 kg of hydroturpentine are obtained from 1000 kg of resin. The main product of resin distillation is rosin with 866.2 kg that is considered a co-product since the sale of rosin gives good economic profits.

The investment cost of the plant has been estimated to be 3 879 515 € using the economic estimation tool of the software Aspen.

## 3.2. Life cycle assessment (LCA)

The Product Environmental Footprint (SIMA PRO EF Method (adapted) version v1.01) was the chosen method for the environmental impact assessment. This methodology has been proposed by the European Commision's Joint Research Center

Table 3 Main properties of the outlet liquid streams from the DIST column (turpentine) and the HYD-REAC reactor (hydroturpentine) and of Jet A-1

| Property name in Aspen | Turpentine | Hydroturpentine | Jet A-1 (ASTM) |
|---|---|---|---|
| Density (at 15 °C) (kg $m^{-3}$) | 862.9 | 859.7 | 783.6 (775–840) |
| Average boiling point (°C) | 152.3 | 169.81 | (205–300) |
| Flash point (°C) | 23.24 | 47.87 | 47.87 (>38) |
| Kinematic viscosity (at −20 °C) ($mm^2$ $s^{-1}$) | 0.78 | 1.78 | 1.78 (<8) |
| Lower heating value (mass basis at 15 °C) (MJ $kg^{-1}$) | 44.64 | 43.1 | 43.1 (>42.8) |
| Energy density (GJ $m^{-3}$) | | 37.05 | 33.77 |
| Freezing point (°C) | <90 | <90 | −69.2 (−47) |

Table 4 Heat duty of the main equipment of the process simulation

| Equipment (Aspen abbreviation) | Energy (MJ $h^{-1}$) |
|---|---|
| Resin heater HEATER | 312.68 |
| Reboiler column DIST | 481.17 |
| Condenser column DIST | −12.62 |
| Heat exchanger rosin ROS-COND | −701.49 |
| Turpentine drier TU-DRY | −32.78 |
| Heat exchanger water $H_2O$-COND | −14.59 |
| Compressor turpentine TU-COMP | 0.25 |
| Hydrogen expansion HY-EXP | −3.77 |
| Heat exchanger hydrogen HY-HEAT | 8.98 |
| Stoichiometric reactor HYD-REAC | −100.12 |
| Heat exchanger hydrogenated turpentine JF-COND | −48.41 |
| Total (absolute value) | 1716.86 |

(JCR) with the goal to provide a common way of measuring environmental performance.[65] The results of the characterization stage of biojet fuel from resin and fossil Jet A1 are shown in Table 6. The relative percentage of impact between Jet A1 and biojet fuel in the different categories can be observed in Fig. 3.

Article 29 of the Directive (EU) 2018/2001 states that the GHG savings from the use of biofuels shall be at least 65% for biofuels consumed in the transport sector compared to fossil fuel emissions. Fossil fuel gas emissions are stated in Article 32 as 94 g $CO_2$ eq. per MJ.[66] The reduction in GHG emissions of the obtained biojet fuel is 93%, which means that biojet fuel obtained from *Pinus* resin would be considered as sustainable following the criteria stated in this European Directive. Taking into account the obtained results for fossil Jet A1 compared to those for biojet fuel included in the Ecoinvent database, the GHG emission reduction for biojet fuel would be 82.96%.

For fossil jet fuel, there is only one category that has a negative environmental impact: the water scarcity, mainly due to the water discharge from petroleum extraction. There are five environmental categories which clearly showed a higher environmental impact for production and combustion of biojet fuel: (1) non-cancer human health effects, being 123% higher for biojet fuel; (2) freshwater eutrophication, being 188% higher for biojet fuel. (3) Resource use, minerals and metals, being 190% higher for biojet fuel (4) climate change due to biogenic sources, being 212% higher for biojet fuel. This is mainly due to biogenic methane generated during the wastewater treatment (52%). (5) Climate change due to land use and transformation, being 1260% higher for biojet fuel. This is mainly due to higher $CO_2$ emissions during land transformation through all the life cycle stages of biojet fuel. This land use and transformation includes

Table 5 Mass balance of the process simulation

| Input | | | Output | | |
|---|---|---|---|---|---|
| | Amount (kg $h^{-1}$) | Stream | | Amount (kg $h^{-1}$) | Stream |
| Resin | 1000 | Feed | Water | 5.2 | $H_2O$-out |
| Hydrogen | 2.1 | HY-Feed | Rosin | 866.2 | ROS-out |
| | | | Hydroturpentine | 129.0 | Jet-out |
| | | | Column heads | 1.7 | Residue |
| Total | 1002.1 | | | 1002.1 | |

Table 6 Results of the impact assessment for biojet fuel and fossil fuel Jet A1

| Environmental categories | Unit | Biojet fuel | Jet A1 |
|---|---|---|---|
| Climate change | kg $CO_2$ eq. | 0.00585502 | 0.08310723 |
| Ozone depletion | kg CFC11 eq. | $7.31 \times 10^{-10}$ | $1.88 \times 10^{-8}$ |
| Ionising radiation HH | kBq U-235 eq. | 0.00115258 | 0.00519663 |
| Photochemical ozone formation HH | kg NMVOC eq. | $1.94 \times 10^{-5}$ | $7.41 \times 10^{-5}$ |
| Respiratory inorganics | Disease inc. | $3.09 \times 10^{-10}$ | $8.96 \times 10^{-10}$ |
| Non-cancer human health effects | CTUh | $4.64 \times 10^{-10}$ | $6.43 \times 10^{-10}$ |
| Cancer human health effects | CTUh | $2.13 \times 10^{-11}$ | $1.73 \times 10^{-11}$ |
| Acidification terrestrial and freshwater | mol $H^+$ eq. | $4.26 \times 10^{-5}$ | 0.00017508 |
| Eutrophication freshwater | kg P eq. | $9.17 \times 10^{-7}$ | $4.88 \times 10^{-7}$ |
| Eutrophication marine | kg N eq. | $5.71 \times 10^{-6}$ | $1.52 \times 10^{-5}$ |
| Eutrophication terrestrial | mol N eq. | 0.00037422 | 0.00048029 |
| Ecotoxicity freshwater | CTU eq. | 0.00574437 | 0.0107381 |
| Land use | Pt | 0.03887146 | 0.0638037 |
| Water scarcity | $m^3$ depriv. | 0.00163186 | −0.00025055 |
| Resource use; energy carriers | MJ | 0.11227475 | 1.1527799 |
| Resource use; mineral and metals | kg Sb eq. | $1.23 \times 10^{-8}$ | $6.46 \times 10^{-9}$ |
| Climate change – fossil fuel | kg $CO_2$ eq. | 0.00583319 | 0.08310207 |
| Climate change – biogenic | kg $CO_2$ eq. | $8.75 \times 10^{-6}$ | $4.12 \times 10^{-6}$ |
| Climate change – land use and transform | kg $CO_2$ eq. | $1.31 \times 10^{-5}$ | $1.04 \times 10^{-6}$ |

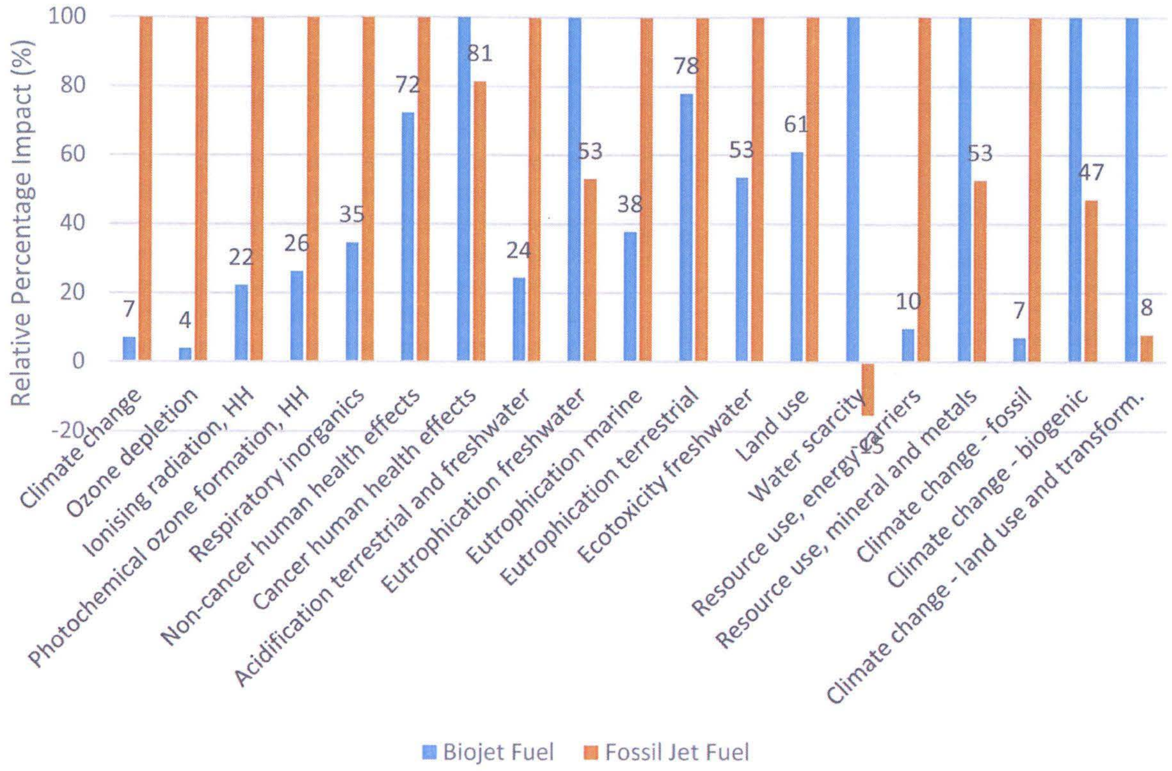

Fig. 3 Relative percentage impact for biojet fuel and fossil Jet A1 in the environmental categories considered in the Product Environmental Footprint Methodology.

that affected by electricity production mainly due to hydraulic electricity production which accounts for 86% of the total impact in this category.

### 3.3. Environmental and production cost assessment

**3.3.1 Environmental and production costs of biojet fuel *versus* Jet A1.** The production cost of biojet fuel, taking into account the environmental externalities, shows that the cost of biojet fuel is 0.60 € per kg (Fig. 4), while if the environmental externalities are not considered, it would be 0.54 € per kg. It is observed that the major cost is the labour cost (0.32 €). The remaining costs are the forest exploitation auction cost (0.12 €), the operation cost (0.04 €), and the transport cost (0.06 €).

The costs associated with the resin extraction amount to 0.32 € of the total, 0.19 € being the resin worker's wage and 0.13 € being the cost of the forest exploitation auction (other costs in Fig. 4). These costs, after externalities, are the ones with the highest influence on the process. The main costs among externalities are: the one associated with electric production from hard coal that accounts for 15% (0.0091 €), and the one associated with the biojet fuel combustion being 12%. Labour costs include the labour cost of the resin harvesting (0.19 €) and the labour cost of the production process (0.13 €). Operational costs include energy (0.02 €) and hydrogen (0.02 €). Transport costs account for the remaining 0.06 €.

The production cost used for fossil Jet A1 is 0.394 € per kg.[67] As usual, the biofuel cost without taking externalities into account (0.54 € per kg) is higher than that of fossil fuel (0.41 € per kg). When externalities are taken into account in both cases, the cost of 1 kilogram of biojet fuel is almost 0.2 € below the price of 1 kg of fossil Jet A1 (22% lower). This is because the environmental impact of fossil Jet A1 is higher than that of biojet fuel, and therefore, its externalities are higher as well (0.37 € *vs.* 0.06 €). As expected, the environmental externalities associated with the emissions from the combustion of fossil fuels, with 0.203 € per kg, is the main contributor to externalities in fossil Jet A1 (56%).

**3.3.2 Influence of resin productivity on production cost.** Since the forest exploitation auction costs and the resin harvester's wage were two of the parameters that influenced most in the final cost of biojet fuel, different scenarios were proposed varying the productivity of the pine and the performance of the resin harvester. The best scenario is one in which the production of resin per pine and the worker's performance increase until 6 kg per tree per year.

For the sensitivity analysis, the resin production per pine will vary among 2, 4, and 6 kg. The usefulness of this simulation is not only to see how these parameters affect the cost, but also to determinate the cost that biojet fuel would have with low resin production, since there may be years wherein, due to weather conditions, the yield could be lower than expected.

As the resin production increases, the labour wage expressed as euros per kilogram would decrease (because the resin harvester would have the same wage independently of the mass

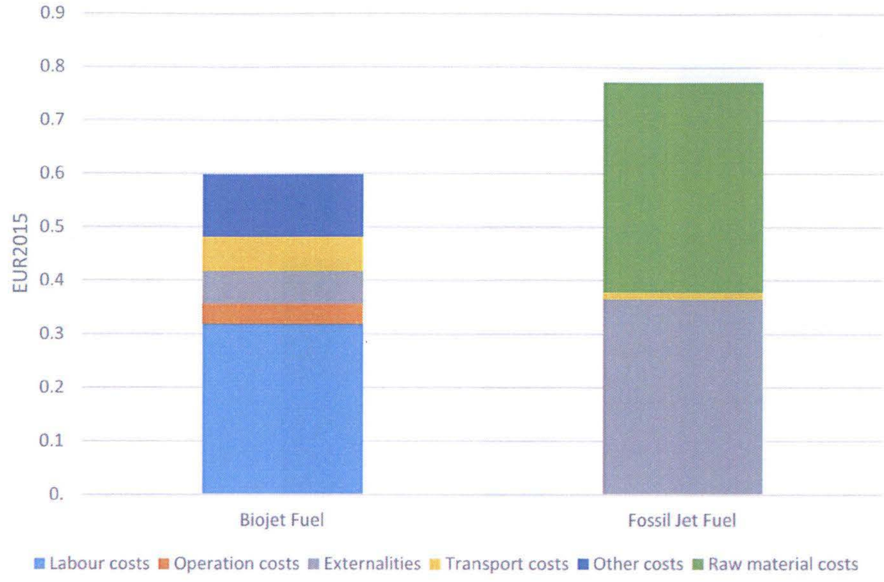

Fig. 4 Final cost of biojet fuel compared with fossil Jet A1.

Table 7 Variation of wage, forest exploitation auction costs and biojet fuel production costs (with and without externalities) per kilogram of resin collected with pine productivity

| Resin collected (kg per pine) | Labour time (h) | Performance (kg h$^{-1}$) | Wage (€ per kg) | Forest exploitation auction cost (€ per kg) | Biojet fuel production cost (with externalities) (€ per kg) | Biojet fuel production cost (without externalities) (€ per kg) |
|---|---|---|---|---|---|---|
| 2 | 0.088 | 22.73 | 0.35552 | 0.225 | 0.902 | 0.804 |
| 4 | 0.088 | 45.45 | 0.17776 | 0.113 | 0.6 | 0.54 |
| 6 | 0.088 | 68.18 | 0.11851 | 0.075 | 0.497 | 0.44 |

of resin collected), and the forest exploitation auction costs would be lower (as the forest exploitation auction costs are the same independent of the productivity of pines). Table 7 shows the variation in the wage of a resin harvester and the forest exploitation auction costs based on the kilograms of resin collected from each pine.

The decrease in the personnel and forest exploitation auction costs together with the costs of externalities has significantly reduced the cost of biojet fuel (Fig. 5). The cost of producing biojet fuel with a productivity of 2 kg per tree per year would be 0.902 € (including environmental externalities), more than the cost of fossil Jet A1 (0.772 € with externalities). This cost decreases for a productivity of 6 kg per tree per year until 0.497 € (including externalities). If environmental externalities are not considered, the biojet fuel obtained from pines with a productivity of 2 kg per tree per year would have a cost of 0.84 €, being double that of the fossil Jet A1 (0.41 € per kg). For a productivity of 4 kg per tree per year, the cost would be 0.54 € per kg (132% higher). For a productivity of 6 kg per tree per year, the cost would be 0.44 € per kg, a little higher than the cost of fossil Jet A1. This means that biojet fuel obtained from resin could almost be competitive for a pine productivity higher than 6 kg per tree per year. It is important to note that productivity variation between 2 and 4 kg per tree per year influences the final cost more (34% drop) than variation in the productivity from 4 to 6 kg (17% drop).

Estimated $CO_2$ eq. emissions are lower compared to other biojet fuels. For example, a recent article[68] studies the $CO_2$ eq. emissions following the Directive (EU) 2018/2001 methodology. Results show that biojet fuel obtained *via* the alcohol-to-jet (ATJ) process generates 75 g $CO_2$ eq. per MJ, while the hydroprocessed ester and fatty acid (HEFA) process resulted in 18 g $CO_2$ eq. per MJ. Another recent work assessed the biojet fuel obtained from the gasification and Fischer–Tropsch process (GFT) and obtained emissions of 20.14 g $CO_2$ eq. per MJ.[69] The main difference between the biojet fuel obtained from hydrogenation of turpentine and biojet fuels obtained from other feedstocks and processes is the simplicity of the chemical process. Turpentine has chemical compounds that can almost comply with jet fuel specifications. After water removal, hydrogenation, and blending, a drop-in biojet fuel is obtained.

Environmental cost assessment has been scarcely used to assess biojet fuel since there was a poor scientific consensus to consider externalities, and most authors have decided to only account for the cost of $CO_2$ eq. emissions. The Environmental Prices methodology is relatively new (available in SimaPro 9.0 released in 2019[70]), so few studies on biofuels have used it for assessing the environmental cost of the process combining the

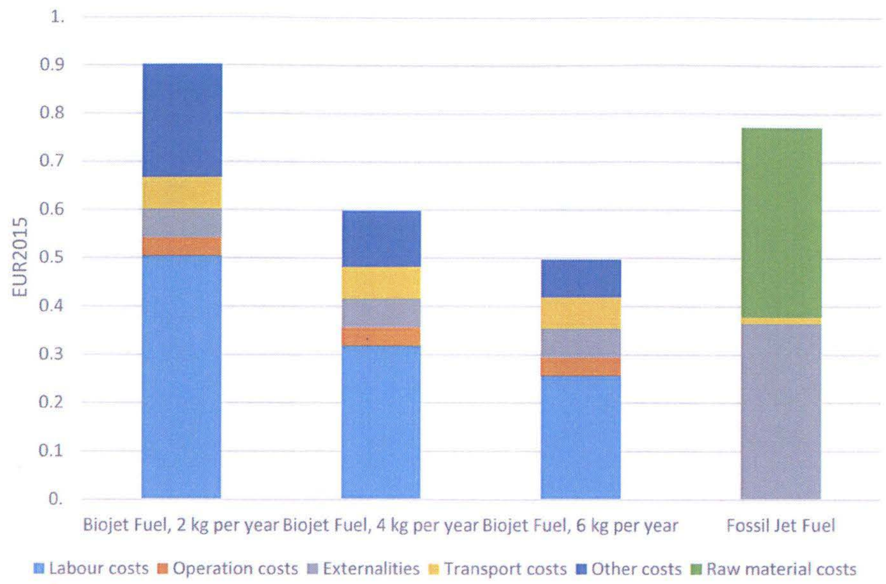

Fig. 5 Final cost of biojet fuel depending on the productivity of the pine.

internal and the external costs of the process.[71] Yadav *et al.*[72] studied the environmental impact assessment of methanol production from wood biomass through different production processes and obtained an environmental cost ranging from 0.044 to 0.023 € per kg, lower than the values obtained in this study that ranges between 0.098 and 0.057 € per kg depending on the productivity of the pines. It is difficult to compare such values since the production processes are different, and they do not account neither for transport nor for combustion.

Nevertheless, if the cost without externalities (0.54 € per kg) is compared to other studies, it is clear that production of hydrogenated turpentine is a good alternative. Diederichs *et al.*[73] analyzed different biojet fuel routes and concluded that the minimum selling price was the lowest for the HEFA process. For example, a thorough study of HEFA production[68] stated a final cost of 0.75 € per L, in good agreement with the obtained results (see Table 7). The reason of this lower price is the simpler chemical transformation needed, and therefore, the lower costs of equipment, materials, and energy.

## 4. Conclusions

The main conclusions attained in this research are:

- For a production of 4 kg of resin per tree per year, the cost of biojet fuel is 0.60 € per kg taking into account environmental externalities and 0.54 € per kg without them. By varying the pine productivity to generate resin, the cost is almost competitive compared to that of fossil Jet A1 for 6 kg of resin generated per tree per year, if the costs for environmental externalities are not taken into account (0.44 € per kg *vs.* 0.41 € per kg). If environmental externalities are included, biojet fuel is already competitive for 4 kg of resin produced per tree per year (0.60 € per kg for biojet fuel *vs.* 0.77 € per kg for fossil fuel).

- The cost of biojet fuel is closely linked to the amount to be invested in labour to harvest resin. As this is done manually, the cost is very high at low resin productions. Worker and pine yields strongly influence the cost of biojet fuel. For the cost of biojet fuel to become competitive, it is important to increase the productivity of resin harvesters and the productivity of the pine to generate resin.

- For a medium production of 4 kg of resin per tree per year, GHG emissions are reduced by 93% with respect to the reference value set by the Directive (EU) 2018/2001, a fairly high value compared to other biofuels.

Because of its emissions, cost, and performance, the biojet fuel obtained from pine resin through turpentine hydrogenation should be considered as a sustainable aviation fuel.

## Conflicts of interest

■■■■ 10

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