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Evaluating sawdust-based bioethanol and pyrolysis products in the European Union: Feedstock availability, life cycle assessment, and techno-economic analysis

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ABSTRACT

The significance of biomass-derived biofuels in global transport is increasing due to their perceived environmental advantages and policies with binding use targets. This study conducted a comprehensive sustainability analysis of sawdust-based bioethanol in the European Union, encompassing evaluations of sawdust availability, techno-economic assessment (TEA), and global warming potential (GWP), including land use and land-use-change-related GWP (GWP-LULUC). It was found that bioethanol production based on average annual sawdust potential could replace only 0.5 % of total fuel consumption in the EU transport sector in 2021, provided that all the sawdust was used for this purpose. The TEA calculations indicated that, while technically feasible, the economics of sawdust-based bioethanol production are not favourable based on this research's assumptions. Pyrolysis-based bioproducts showed better profitability. The economics of bioethanol production depends greatly on the sawdust cost, which was shown by the sensitivity analysis conducted. The GWP results highlighted the potential environmental benefits of ethanol-blended fuels such as E20 (20 % bioethanol with gasoline) and E85 (85 % bioethanol with gasoline), demonstrating reductions of 18 % and 78 % in fossil GWP impacts compared to petrol respectively. Examining GWP-LULUC unveiled a notable sequestration effect, primarily due to increased carbon storage in forests. However, these effects vary depending on the production year, country of origin, or soil type. In the context of this study, sawdust-based bioethanol demonstrated the potential to replace some fossil fuels, offering technical feasibility and considerable environmental benefits. However, it is not economically feasible and is highly influenced by policy changes and competition among different sectors.

1. Introduction

The role of biomass-based biofuels in the global transport sector is increasing significantly due to their perceived advantages such as their ability to minimise global warming potential (GWP), advance energy security, reduce our dependence on fossil fuels, and their renewability (Thanigaivel et al., 2022; Ghani and Gheewala, 2021; Qian et al., 2024). The European Union (EU) has also committed to significant reductions in carbon dioxide emissions along with substantial growth in the use of renewable energy sources. The transport industry is being scrutinised closely because it is responsible for around 25 % of the EU's greenhouse gas (GHG) emissions (EU, 2023).

The EU has adopted numerous policies and laws to promote the

production and use of renewable transport fuels. The European Green Deal targets a 90 % reduction in transport emissions (COM, 2019). The 2030 Climate target plan aims to increase renewable energy in transport from 6 % in 2015 to 24 % by 2030 by means of electric vehicles, advanced biofuels, and other renewable and low carbon fuels (COM, 2020). The updated Renewable Energy Directive establishes a combined binding sub-target of 5.5 % for advanced biofuels (i.e. biofuel from non-food-based feedstocks) and non-biological-origin renewable fuels (i.e. mainly synthetic fuels from renewable hydrogen and hydrogen sources) in the proportion of renewable energies supplied to the transport sector (EU, 2023).

Despite being a promising source of energy, forest-based biofuels, like other biomass fuels, face concerns regarding their sustainability and

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effectiveness in addressing various issues (Gheewala et al., 2016). The forests in the EU are limited, and these resources therefore need to be utilised wisely in only environmentally sustainable applications that are also technologically and economically sound (Osman et al., 2024). To address these concerns, an integrated assessment of forest biomass resource availability, coupled with a techno-economic assessment (TEA) and a life cycle assessment (LCA) would be the appropriate method (Silartruksa and Gheewala, 2009; Vazifeh et al., 2023; Zhang et al., 2024). Evaluating the sustainability and feasibility of utilising forest resources for biofuel production significantly depends on understanding their availability, ensuring responsible resource management, and minimising negative environmental impacts. Anttila and Verkerk (2022) reviewed recent assessments on forest biomass availability in Europe. They concluded that the forests of the EU could sustain higher harvesting levels than in the past, but this would come with the cost of lower carbon storage and impacts on other forest functions. In addition, there are large differences between regions and biomass assortments. Furthermore, TEA provides a crucial understanding to assess the economic viability of biofuel production from forests, encompassing capital costs, operational expenses, profitability, and resource efficiency. Moreover, these analyses inform policy development, shape sustainability certifications, and contribute to an integrated assessment approach that comprehensively evaluates the sustainability of biofuel systems.

Forest-based fuels result in lower GWP than fossil-based fuels, and most of the impacts come from the biofuel production stage (e.g. in the studies conducted by Feinauer et al., 2021 and Yacout et al., 2021). Biofuel options could successfully achieve the decarbonisation targets such as through the FuelEU Maritime initiative (e.g. in Watanabe et al., 2022). Economic feasibility may depend on the scale of production and the cost of feedstocks (Ashokkumar et al., 2022). Furthermore, renewable transport fuel obligation policies can significantly improve the financial feasibility of biofuels (e.g. in Michaga et al., 2022). Withers et al. (2015) studied the carbon debt incurred by transportation biofuels derived from woody biomass sourced from managed forests. Other relevant studies include Ganguly et al. (2018), which examined the GWP impacts of wood-based biojet fuel, and Puricelli et al. (2022), which analysed the climate change impacts of various fuels, including biomethanol produced from willow chips. However, none of the previous studies have comprehensively addressed the combined significance of forest resource availability and TEA in the context of biofuel LCA.

Therefore, considering the vital role of biomass-based biofuels, such as from wood residues, in the EU's renewable energy and climate goals as mentioned above, this particular study is aimed at evaluating the feasibility of producing bioethanol from sawdust in the EU, considering potential availability, techno-economic feasibility, and environmental sustainability. Saw dust was chosen as the wood residue raw material because sawmill industry in the EU is well-established, and detailed statistics on the production volumes are easily available (FAO, 2024). Sawmills utilise large volumes of timber, which means that the logistics are highly developed and optimised. Thus, it is plausible to assume that the amount of sawdust produced, as well as its geographical distribution, can be estimated; indeed, sawdust availability in the EU has been assessed by, e.g., Saal (2010), Saal, 2010a and Dees et al. (2017). The latest assessment known by the authors (Dees et al., 2017) was based on sawnwood production data from 2010 to 2014, suggesting that up-to-date estimate would be necessary.

When considering refining forest-derived biomass to biofuels, further advantage of sawdust compared to e.g. logging residues is its chemical composition: derived from debarked roundwood, sawdust contains virtually the same components as the wood material; hence, bark-derived impurities are present only to minor amounts. This is highly advantageous, as wood bark is reported to notably decrease the overall yield of bioethanol produced from forest residues (Frankó et al., 2015). Based on this, it was seen justified to choose sawdust as the preferred raw material for bioethanol production when carrying out LCA and TEA

in this work, as well as assessing the availability of the raw material.

The structural components of woody biomass are cellulose, hemicelluloses, and lignin, which make up approximately 95 % of the wood dry matter (Alén, 2000). Bioethanol is produced in fermentation, where sugar is converted to ethanol and carbon dioxide by yeast. The conventional yeast strains can only ferment hexoses, i.e. sugars with six carbons. In wood, the most important source of hexoses is cellulose, which can be hydrolysed to glucose monomers (Viikari and Alén, 2011). Cellulose content in wood dry matter is ca. 40 %; thus, unfermented wood residue forms a major side-stream. To enhance the resource-efficiency of the biofuel production, thermochemical conversion process of the fermentation residue principally to pyrolysis oil was considered a credible option (Konttinen et al., 2011). Therefore, further analysis of this process concept was chosen as a research topic in this work.

To summarise: we are not aware of any published LCA and TEA research paper concerning biofuel production in the EU, also including an availability assessment of the forest-based raw material. To address the mentioned research gap, this study deals with the following research questions:

- How much sawdust is available in the EU for bioethanol production and to what extent this resource can fulfil the fuel needs?
- How is the techno-economic feasibility of combined bioethanol and pyrolysis oil production from sawdust?
- What is the life cycle environmental sustainability performance, in terms of GWP, particularly in relation to GWP-LULUC carbon sequestration, of bioethanol compared to fossil fuels?

Additionally, the study aims to clarify how the findings from an inclusive LCA, integrating forest resource availability and TEA, can contribute to informed policy decisions, advances in industry practices, and the establishment of a more sustainable bioenergy sector.

2. Methodology

This study involves a thorough sustainability analysis of bioethanol in the European Union through an integrated assessment approach, encompassing the following aspects: (1) an estimation of the technical potential of coniferous sawdust; (2) a techno-economic assessment (TEA); and (3) a life cycle assessment (LCA). Detailed methodological information for each of these techniques is provided below.

2.1. Sawdust potential

In this study, we assume that the feedstock of bioethanol originates from the EU. As the amount of sawdust depends (almost) directly on the amount of produced sawn wood, the technical supply potential of conifer sawdust (SDQ) can be estimated when production quantity of sawn wood (PQ) and the ratio of sawdust quantity and product quantity (SDPR) are known (Lindner et al., 2017; Eq. (1)).

$$SDQ = PQ \times SDPR \quad (1)$$

In practise, the potential was estimated as follows:

1. The historical production quantities of coniferous sawn wood (in solid m³) between 2013 and 2022 were retrieved from the FAO (2024) by country and year.
2. Country-level SDPRs were applied to estimate sawdust quantities (Dees et al., 2017).
3. The estimated SDQs were converted to dry tonnes. The basic density varies according to tree species, location within a stem, growing site, tree density, and geographical location. In the biggest producer countries of conifer sawn wood – Germany, Sweden, and Finland – spruce and pine species are dominant. It is impossible to find fully comparable figures for each country. The average value of spruce

and pine sawlogs in Finland (0.4 t/m³) was therefore used (Hakkila, 1966).

2.2. Techno-economic assessment

A techno-economic assessment was conducted for two industrial-scale processes, for which the production schemes were adapted from the literature:

1. Bioethanol manufacture from spruce sawdust consisting of SO₂ assisted steam explosion, enzymatic hydrolysis, fermentation, distillation, and dehydration stages (Palmqvist et al., 1996; Frankó et al., 2015, 2016; Joelsson et al., 2015)
2. Fast pyrolysis with a circulating fluidised bed, in which the raw material is the solid residue from the bioethanol process (Chechurin, 2013; Pienihäkkinen et al., 2021)

Spruce sawdust containing a negligible amount of bark was chosen as the raw material for bioethanol production, as bark is reported to have a notable detrimental effect on bioethanol production (Frankó et al., 2016; Frankó et al., 2015; Joelsson et al., 2015). The general assumptions for the TEA of the processes are given below (bioethanol production: Table 1; pyrolysis process: Table 2); Fig. 1 and Fig. 2 show the production schemes of the bioethanol production process and the pyrolysis process respectively.

The bioethanol production process chosen to be assessed is in line with established technologies. For lignocellulosic biomass, extensive pretreatment processes are needed to overcome the recalcitrance of the lignin-containing matrix, exposing the polysaccharides for hydrolysis and eventual fermentation. Steam explosion is a proven technology (Aggarwal et al., 2022), and SO₂ catalyst is reported to increase the efficiency of bioethanol production for coniferous raw material (Gregg et al., 1998). Separate hydrolysis and fermentation (SHF) is used very widely due to its versatility (Aggarwal et al., 2022). The production volume, 100,000 t/a, is large in the EU, but in the USA even larger production units utilising cellulosic biomass, exist (Broda et al., 2022). In general, due to economy of scale, larger production units in process technology give better economic feasibility.

Estimating the prices of industrial raw materials and products is challenging, because they are fluctuating; also, in many cases the information is restricted due to business reasons. In this work, the prices for sawdust, ethanol, pyrolysis oil, and biochar are estimations made by the authors based on their business contacts and experience.

The pyrolysis process starts by drying the incoming solid hydrolysis residue (from 57 % to 93 % DMC). Thereafter, fast pyrolysis is performed, after which the solid products and the fluidised bed sand are separated from the other pyrolysis products in cyclones. The separated solids then enter controlled combustion and are screened to separate the biochar from the sand. Simultaneously, the gaseous product stream from the cyclones is quenched to separate the non-condensable gases from the bio-oil. Some of the bio-oil is separated as the product from the process,

Table 1
General assumptions for the TEA of the bioethanol process; o.d. = oven dry.

Items	Value
Annual production of 99 % bioethanol	100,000 t/a
Annual time of operation	344 days/a; 8255 h/a
Raw material	Spruce sawdust
Ethanol production technology	SO ₂ assisted steam explosion Enzymatic hydrolysis Separate hydrolysis and fermentation (SHF)
Spruce saw dust price (€/o.d. t)	40
Dehydrated ethanol selling price (€/t)	990
Dehydrated ethanol selling price (€/m ³)	781

Table 2
General assumptions for the TEA of the pyrolysis process.

Items	Value
Annual time of operation	344 days/a; 8255 h/a
Raw material	Solid stream from bioethanol production
Pyrolysis technology	Fast pyrolysis, circulating fluidised bed
Bio-oil selling price (€/t)	580
Biochar selling price (€/t)	1200

while most of the bio-oil is circulated in the quencher for continuous cooling of the gaseous products from the pyrolysis. The non-condensable gases are circulated back to the pyrolysis unit, where the flammable gases (H₂, CO, short-chained hydrocarbons) are combusted to aid in sustaining the high operating temperature (500–550 °C). The size of the assessed pyrolysis oil production process is determined by the size of the bioethanol process, from where the pyrolysis process's raw material originates. Fast pyrolysis is an established technology: several production facilities are reported to be running, estimated annual production of pyrolysis oil globally exceeding 180,000 t (2021) (Osman et al., 2024).

The chemical composition of the sawdust dry matter is presented in Table 3.

2.2.1. Material balance of the production processes

The assessment of the process feasibility was started by constructing material balances for industrial-scale processes based on earlier publications (Chechurin, 2013; Joelsson et al., 2015; Frankó et al., 2016; Pienihäkkinen et al., 2021). The balances were calculated using Excel software (Microsoft). The targeted annual production of the bioethanol plant was set to 100,000 t of dehydrated ethanol (99 wt%). Certain material losses were assumed in the process; they include sawdust screening (1 wt% loss) and chemical reactions to inert products, as well as losses due to spillages in different process stages (9 wt% loss in total of the chemical components in the sawdust). The yields of the most important process steps in the bioethanol process are presented in Table 4.

The amounts of the most important chemical and utility additions in the bioethanol process are presented below (Table 5).

The solid material separated after saccharification is used as the feedstock for the pyrolysis process. Table 6 lists the assumed yields for the products in the pyrolysis process. Based on the material balance constructed for the bioethanol process, the total incoming material stream to the pyrolysis was assumed to be c. 277,000 t/a, corresponding to 33.6 t/h (DMC = 57 %).

2.2.2. Capital expenditures (CAPEX)

Capital expenditures (CAPEX) were based on the investments required for the equipment and other cost items required to construct an industrial plant. The basis of cost assessment was the purchasing cost for the main equipment; thereafter, the percentage method was used for the other investment costs. Databanks from an Aspen In-Plant Economic Analyser (APEA) were used to assess the equipment costs, and the Chemical Engineering Plant Cost Index (CEPCI) was applied to adjust process plant construction costs for the present. The percentages and cost items considered can be found in Table 8.

2.2.3. Operating expenditures (OPEX)

The operating expenditures (OPEX) of the processes include variable costs (raw material costs and utilities) and fixed costs (e.g. personnel and insurance costs) that are caused by running the process. No cost was assumed for the raw material of the pyrolysis process, as the solid residue originates in the bioethanol process. Like the investment estimate, the figures for operational costs are retrieved and estimated from earlier studies; as explained earlier, in this case, all the prices were also corrected to be in line with today's cost levels. The considered OPEX items are presented in Table 9.

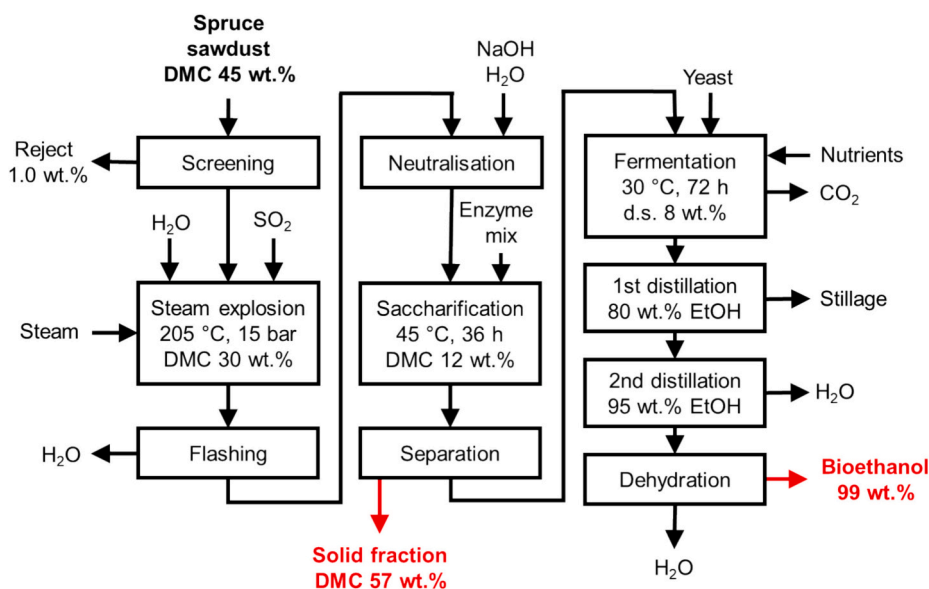


Fig. 1. Process scheme of bioethanol production. The process was adapted from Frankó et al. (2016). The final products are indicated in red; the residue from the saccharification (Solid fraction) is the feedstock for the pyrolysis process.

DMC = dry matter content; d.s. = dissolved solids; EtOH = ethanol. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

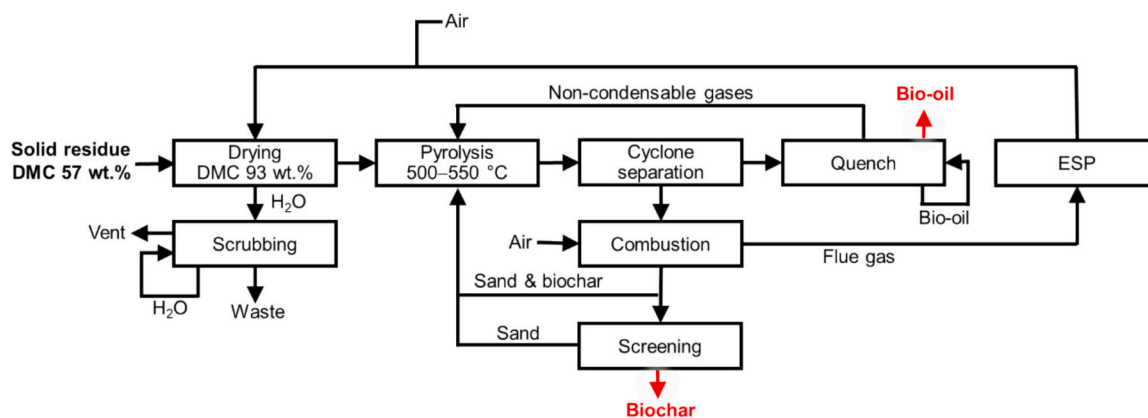


Fig. 2. Scheme of the pyrolysis process designed based on Pienihäkkinen et al. (2021) and Chechurin (2013); for the TEA, the solid residue of the bioethanol process was set as the feedstock of the pyrolysis. The feedstock is dried to 93 % DMC before being pyrolysed. The final products are bio-oil and biochar, indicated in red. ESP = electrostatic precipitator. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

Chemical composition of the assumed raw material, spruce sawdust dry matter. The dry matter content (DMC) of the sawdust was assumed to be 45 % (Alén, 2000).

Component	Dry matter [wt%]
Lignin	33.8
Cellulose	40.0
Hemicelluloses	22.6
Other (extractives, inorganics)	3.6
TOTAL	100.0

Table 4

Assumed yields of the process steps during bioethanol production; data from Frankó et al. (2016) and Joelsson et al. (2015) were utilised in the calculations. The yields refer to the original raw material (spruce sawdust) dry matter unless otherwise indicated.

Process step	Yield [wt%]
Sawdust screening	99
Steam explosion, SE	90
Total dissolved material in SE and saccharification	59
Solid material after SE and saccharification	31
Total dissolved hexoses (total dissolved sugars)	47 (53)
Fermentation of hexoses, yield from theoretical	90
Distillation 1, yield from incoming ethanol	90
Distillation 2, yield from incoming ethanol	99
Dehydration, yield from incoming ethanol	99

2.2.4. Profitability assessment and sensitivity analysis

Profitability was estimated by the net present value (NPV) calculation, which takes investment and revenues into account. The discounted cash flows were determined for discount rates of 2, 6, and 12 over the investment’s lifetime. The sensitivity analysis was determined based on sawdust, enzyme mix, and yeast prices using the AssessCCUS calculation tools (AssessCCUS, 2024).

Table 5

The most important chemical and utility additions in the bioethanol process. HP = high pressure; d.s. = dry solids.

Process step (chemical/utility)	Amount [g/kg d.s.]
Steam explosion (HP steam)	300
Steam explosion (SO ₂)	15
Saccharification (enzyme mix)	1.88
Fermentation (yeast)	1.35
Nutrient ((NH ₄) ₂ HPO ₄)	0.135

Table 6

Assumed yields of the process steps during pyrolysis; adapted from (Pienihäkkinen et al., 2021). No losses were assumed in the process.

Pyrolysis products	Yield [wt%]
Char	40
Pyrolysis oil	40
Reaction water (mixed with pyrolysis oil)	10
Gaseous compounds	10

The NPV and the sensitivity analysis were only determined for bioethanol production.

2.3. Life cycle assessment

The goal of this study is to evaluate the GWP impact of sawdust-based bioethanol in the European Union, as well as to analyse land use and land-use-change-related GWP (GWP-LULUC) due to the production of bioethanol. The study was conducted from cradle to grave, including sawdust production (i.e. forest management and harvesting, and saw milling), transport, bioethanol production, blending with conventional petrol, and its ultimate use in vehicles. The functional unit of the study was the use of 1 l bioethanol from sawdust. The study followed ISO 14040:2006 and 14,044:2006. SimaPro (9.6) was used for LCA modelling and processing of the results.

The production system for forestry comprises site preparation, natural regeneration or planting, stand management, and finally, the harvesting of forest wood, which includes cutting, off-road transport, and the possible chipping or crushing of trees. Sawlogs are sent for sawmilling producing sawn timber and sawdust (please refer to Fig. 3). The details of bioethanol production are already described in the TEA.

The cradle-to-grave system boundary for bioethanol considered in this study is shown in Fig. 4. Sawdust is transported to the bioethanol production plant, where bioethanol is produced, while solid residues are further processed in a pyrolysis plant to produce bio-char and bio-oil as co-products. The bioethanol is then blended with petrol in different percentages. In this study, we have considered E20 (i.e. a 20 % blend of bioethanol with petrol on a volumetric basis) and E85 (i.e. an 85 % blend of bioethanol with petrol on a volumetric basis). The blended fuel is then transported and used in vehicles.

During bioethanol production, the pyrolysis process generates biochar and bio-oil as co-products. To reflect this, the economic allocation

model assigns respective GWP shares to bioethanol (42 %), biochar (34 %), and bio-oil (24 %). The focus of the article is to investigate the GWP of bioethanol production from forest residue. Therefore, the system boundary includes the end of use of bioethanol and exclude the use of bio-oil and biochar from pyrolysis process. The inventory data primarily originated in the TEA, while information regarding chemical and materials production, as well as emission studies, was gathered from sources such as the Ecoinvent (v 3.10) database and literature reviews. The processes used in the LCA modelling are presented in the supplementary materials Table S2. The impact assessment utilised the IPCC 2021 global warming potential (GWP) 100 (V1.02) method (IPCC, 2021). GWP-LULUC emissions were calculated using the framework outlined by Leinonen (2022), detailed in Section 2.2 below. This study did not consider GWP impact from wastewater treatment.

2.3.1. Including the land use and land-use-change-related GWP (GWP-LULUC) impacts

The IPCC, 2014 impact assessment method calculates the GWP in three categories, including fossil-related global warming potential (GWP-fossil), biogenic-related global warming potential (GWP-biogenic), and land use and land-use-change-related global warming potential (GWP-LULUC). However, despite the importance of GWP-LULUC in LCA (ISO, 2018), GWP-LULUC calculated using the ecoinvent database in SimaPro does not fully capture these impacts, especially in considering the changes in carbon stock in forests. We have therefore calculated the GWP-LULUC following the general framework presented by Leinonen (2022). N₂O emissions from organic soils are included in GWP fossil impacts (IPCC, 2014).

GWP-LULUC emissions consist of both the emissions and removals of biogenic carbon resulting from land use (LU), land-use changes (LUC), and management practices (Lehtilä et al., 2025). Here, we have adopted a mass balance approach to evaluate the GWP-LULUC impacts in accordance with the general framework presented by Leinonen (2022). In this approach, net LULUC emissions over a specific period are allocated to all the products obtained within the same period. The calculations are performed using the following equation (Eq. (2)).

$$GHG_{LULUC} = \frac{\Delta C \times \frac{44}{12} + CH_4 \times 29.8}{C_h} \text{ (kg CO}_2 \text{ eq./kg C)} \quad (2)$$

GWP_{LULUC} represents the LULUC related GWP in kg CO₂ eq./kg C, ΔC shows the change in ecosystem carbon storage in kg C, CH₄ stands for methane emissions from organic soil in kg CH₄, the factor 29.8 is introduced to convert the kg CH₄ to kg CO₂ eq., and C_h represents the harvested biomass carbon in kg C.

GWP-LULUC emissions are calculated by evenly distributing the annual LULUC emissions and removals over the annual harvested carbon. The carbon content of bioethanol is considered part of the harvested carbon. Hence, the GWP-LULUC of bioethanol is evaluated based on its carbon content (i.e. around 0.52 kg C/L of bioethanol). GWP_{LULUC} is closely connected to GWP biogenic, with the latter consistently calculated based on carbon content.

The change in ecosystem carbon storage (ΔC) includes the net

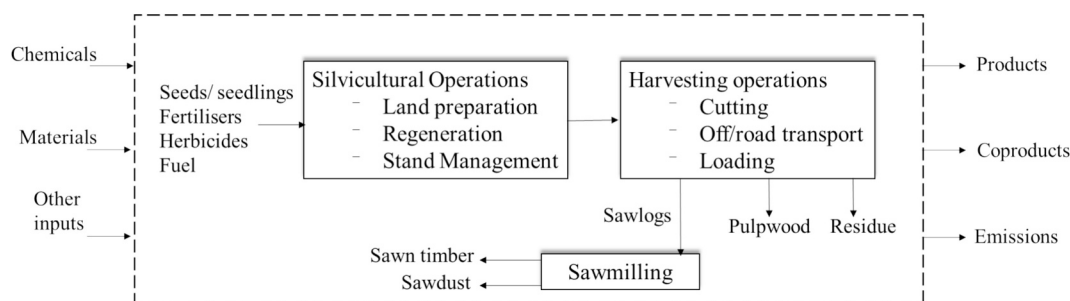


Fig. 3. Production system for forestry.

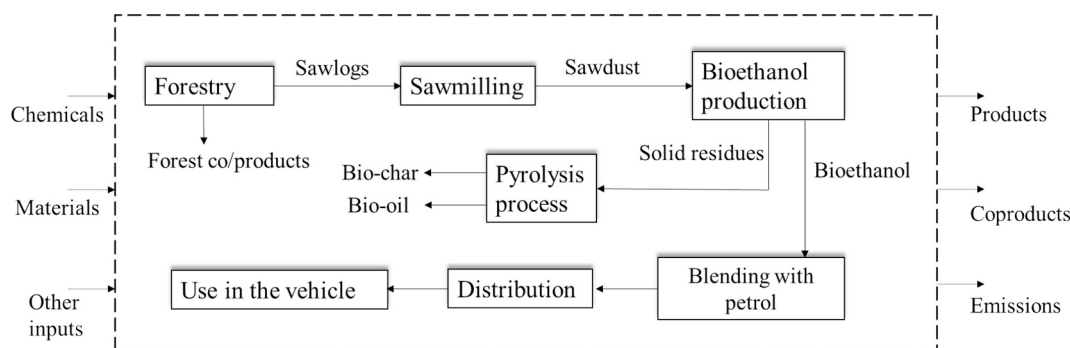


Fig. 4. Product system and system boundaries for forest-based E20 and E85 use.

changes in carbon stock in terms of living biomass, dead organic matter (DOM), and soil carbon (SOC) in mineral and organic lands. ΔC and CH₄ emission values are obtained from the common reporting format (CRF) tables of the IPCC national inventory report (NIR) submissions database (see Table S1 in the supplementary materials). This database provides annual inventories for the parties included in Annex 1 to the UNFCCC convention (UNFCCC, 2023). Here, a top-down approach is used to determine the overall carbon stock change associated with forest management, as quantified in the NIR and then calculate the LULUC emissions and removal of product based on this carbon stock change. The NIR reports are openly accessible and updated annually, thereby enabling LCA users to utilise the most current freely available data.

The information regarding biomass harvesting is sourced from the Eurostat database considering over bark wood removal (Eurostat, 2023c). The harvested biomass was subsequently converted to harvested C using an average wood basic density of 448.5 kg dry weight/m³ (UNECE, 2010), while assuming the carbon content to be approximately 50 % of the dry matter content, as per the IPCC guidelines (IPCC, 2006).

3. Results and discussion

3.1. Sawdust potential

The technical supply potential of conifer sawdust was estimated based on historical production quantities of coniferous sawn wood. The estimates can be considered conservative in the light of the Forest Sector Outlook Study 2020–2040 (Herrmann et al., 2021), which projects a strong increase in sawn wood production in the EU. However, regarding the considerable uncertainties due to climate change and geopolitical development, for example, the estimated supply potentials can be held as an adequate indicator of the order of magnitude for assessing the raw-material base for ethanol production.

The production of coniferous sawn wood grew continuously between 2012 and 2021 (FAO, 2024). To account for the variation in the last ten years, the production in the years corresponding to the minimum (86 Mm³ in 2013) and maximum (104 Mm³ in 2021) production in the EU was used as the basis for the calculation. In addition, the year closest to the average production (97 Mm³ in 2017) was selected. The total estimated technical supply potential of conifer sawdust in the EU based on sawn wood production varied between 9.5 and 11.4 million dry tonnes (Mt). The potential in the average year, 2017, was 10.7 Mt. The highest potentials were estimated for Sweden, Germany, Finland, and Austria:

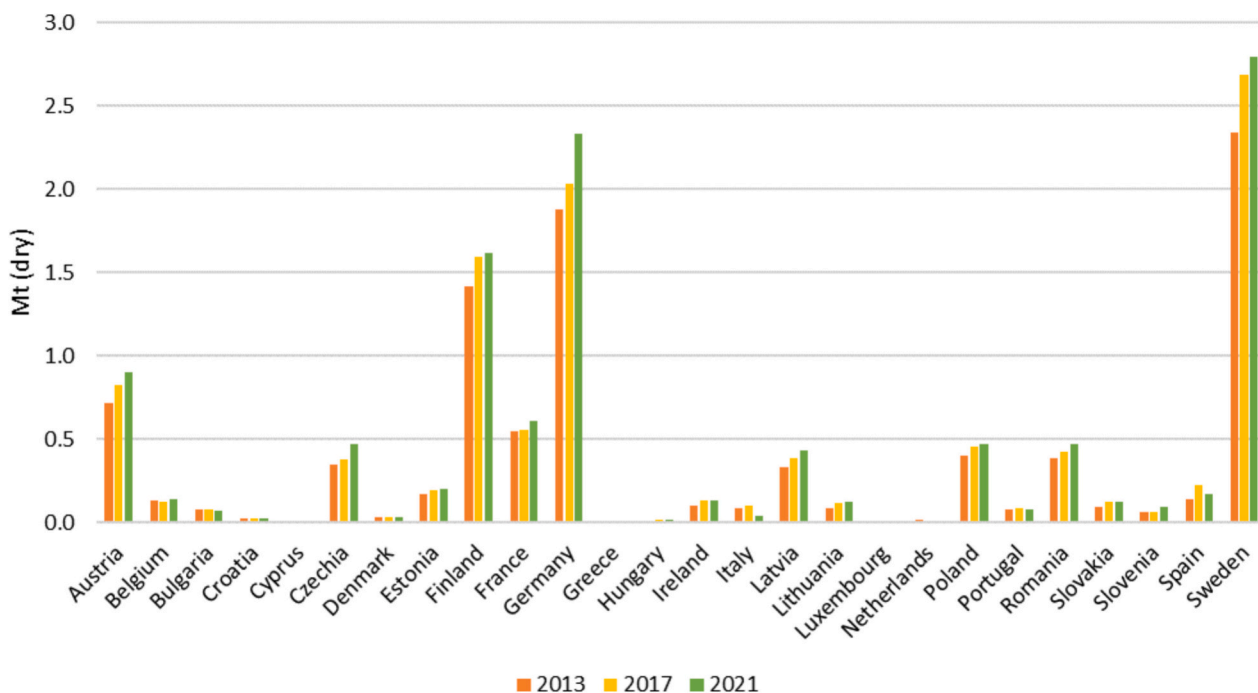


Fig. 5. Estimates of the technical supply potential of conifer sawdust based on sawn wood production in selected years.

2.7 Mt, 2.0 Mt, 1.6 Mt, and 0.8 Mt in 2017 respectively (please refer to Fig. 5).

In addition to sawmills, smaller flows of sawdust come from plywood mills. Non-coniferous species are also utilised in sawmilling. In 2022, the share of non-coniferous sawn wood in the EU was less than 10 %.

The supply potential in proportions are as follows. The total fuel consumption in the EU transport sector in 2021 was nearly 270 Mtoe (Eurostat, 2023b). By assuming 18.6 % efficiency for converting sawdust to ethanol (see Section 3.2), only 0.5 % of the total fuel consumption in the EU in 2021 could be replaced with 10.7 Mt of conifer sawdust. However, sawdust has other established uses. Currently, it is used in the particle board and pulp industries and to produce energy either by direct incineration or via pellets. The demand for sawdust in the pellet industry is high due to EU renewable energy targets, and it is continuing to increase due to the Russian invasion of Ukraine. In respect of the combined sub-target of 5.5 % for advanced biofuels and renewable fuels of non-biological origin set in the RED, sawdust-based ethanol can therefore only play a minor role in the solution.

3.2. Techno-economic assessment (TEA)

The results of the TEA are presented below. We start with the bioethanol process and continue with the pyrolysis process. Finally, the economic figures of the processes are combined.

The material streams of the bioethanol process are presented in Table 7.

The determined CAPEX and OPEX for the bioethanol production are presented in detail in Table 8 and Table 9 respectively.

The results show that bioethanol production is technically viable. However, the economics of the process are not promising: the calculations indicate that the capital investment required is massive. The raw material price was assumed to be €40/o.d. tonne, corresponding to about €20/wet tonne. Currently, this may be an optimistic price for the raw material, especially given the size of the assumed bioethanol plant. The annual sawdust demand of 502 kt corresponds to approximately a fifth of total conifer sawdust production in Sweden in 2017. Collecting this amount would require transport over very long distances. However, even with this raw material price, the relative amount of the raw material price of the overall operating costs of the ethanol production is very high – more than 25 %. Based on the results, another critical raw material for the operating costs is the enzyme mix, amounting to up to 9.3 % of overall operating costs. Moreover, the process's extensive steam consumption contributes significantly to operating expenditures (OPEX): the combined share of the LP and HP steam amounts to 19.1 % of OPEX. This is due to the steam used for the steam explosion, as well as for heating the large volumes of liquids during the hydrolysis and fermentation steps in numerous reactors.

The extremely high capital costs, totalling 405 million euros, are principally due to the very high volume and long residence times of the streams in the process's saccharification and fermentation; the equipment cost covers 29 % of CAPEX. Based on the calculation, the required number of high-volume reactors (volume > 1000 m³) is 15 for the

Table 7

Material streams in the bioethanol process. The overall yield of the process, calculated from the final product and the dry matter of the sawdust raw material, is 18.6 %. DMC = dry matter content; o.d. = oven dry.

Material	Material flow	
	[t/h]	[kt/a]
Sawdust (DMC 45 %)	136	1114
Sawdust (o.d.)	61	502
Hexoses to fermentation (o.d.)	27.9	230
Bioethanol produced (99 wt%)	11.4	95
Solid residue to pyrolysis (DMC 57 %)	33.5	277
Solid residue to pyrolysis (o.d.)	19.0	157

Table 8

CAPEX breakdown (bioethanol). OSBL (outside battery limits) refers to storage and other equipment and utilities, which are not elemental parts of the process equipment (which are referred to as ISBL, inside battery limits).

Cost item	[€M]	[% of eq.]	[% of FCI]
Equipment (delivered)	111.3	100	29
Installation	27.8	25	7
Piping	27.8	25	7
Insulation & painting	13.4	12	3
Instrumentation & controls	22.3	20	6
Electricity	16.7	15	4
Buildings	33.4	30	9
Yard	11.1	10	3
OSBL (outside battery limits)	22.3	20	6
Engineering & supervision	11.1	10	3
Construction & startup	11.1	10	3
Contractors	13.4	12	3
Subtotal	321.7		
Contingency	64.3	20	17
Total FCI	386	[€M]	100
Working capital	19	[€M]	
CAPEX	405	[€M]	

FCI = fixed capital investment.

Table 9

OPEX breakdown (bioethanol). LP = low pressure; HP = high pressure.

#	Items	unit/a	unit	[€/unit]	[€/a]	[% of C _{OP}]
1	Sawdust	502,000	[t]	40	20.1	26.9
2	SO ₂	7000	[t]	600	4.2	5.6
3	NaOH	9000	[t]	250	2.3	3.0
4	Yeast	453	[t]	10,000	4.5	6.1
5	Nutrients	136	[t]	1800	0.2	0.3
6	Enzyme mix	934	[t]	7500	7.0	9.4
	Raw materials				38.3	51.2
7	Steam (LP)	413,000	[t]	20	8.3	11.0
8	Steam (HP)	149,000	[t]	40	6.0	8.0
	Steam total				14.2	19.0
9	Other utilities	20,000	[t]	100	2.00	2.7
10	Electricity	34,000	[MWh]	60	2.04	2.7
	Maintenance & repairs ^a				5.6	7.4
11–11	Variable cost				62.1	83.1
	Salaries & social expenses ^b				2.4	3.2
12	Insurance ^c				7.7	10.3
13	Administration ^d				0.5	0.7
14	Sales & marketing ^d				0.5	0.7
15	R&D ^d				0.5	0.7
16	Security & healthcare ^d				0.5	0.7
17	Quality control ^d				0.5	0.7
18	Fixed cost				12.6	16.9
12–18	Total operating cost, C _{OP}				74.8	100.0

^a 5 % of equipment.

^b 40 persons.

^c 2 % of CAPEX.

^d 4 % of fixed OPEX.

saccharification and 30 for fermentation. As discussed above, the number of the reactors is high, which is also, of course, reflected to the operating costs, resulting in the unfavourable economics of the whole process.

It may be possible to tackle some of the economic challenges by using other technical solutions. For example, choosing simultaneous saccharification and fermentation (SSF) instead of separate hydrolysis and fermentation (SHF) would decrease the number and volume of the required reactors. Moreover, there may also be opportunities to improve the saccharification economics by choosing more efficient enzymes or producing the enzymes on site. However, based on the current results, it

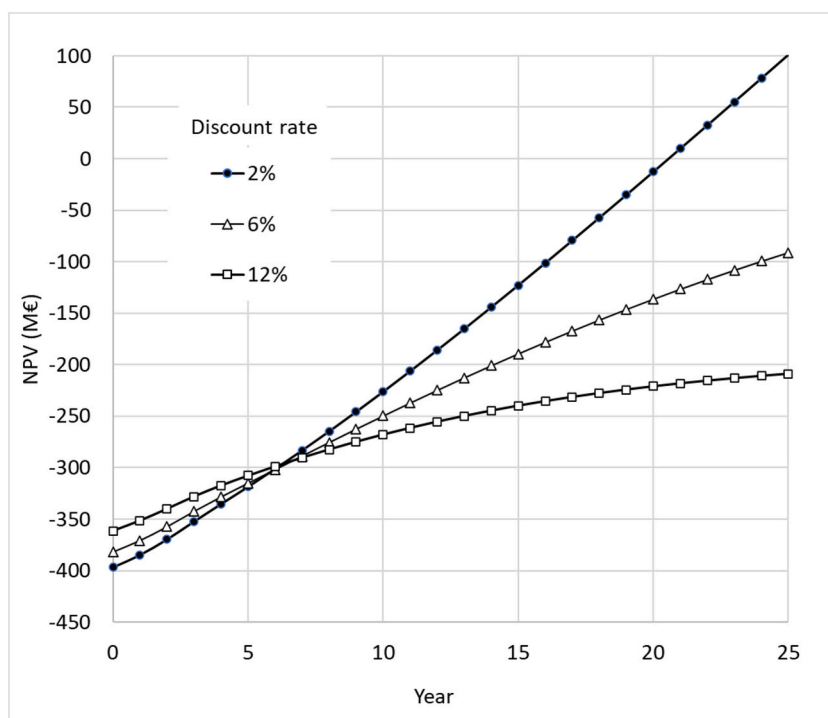


Fig. 6. NPV of the bioethanol process calculated with different discount rates (2 %, 6 %, and 12 %).

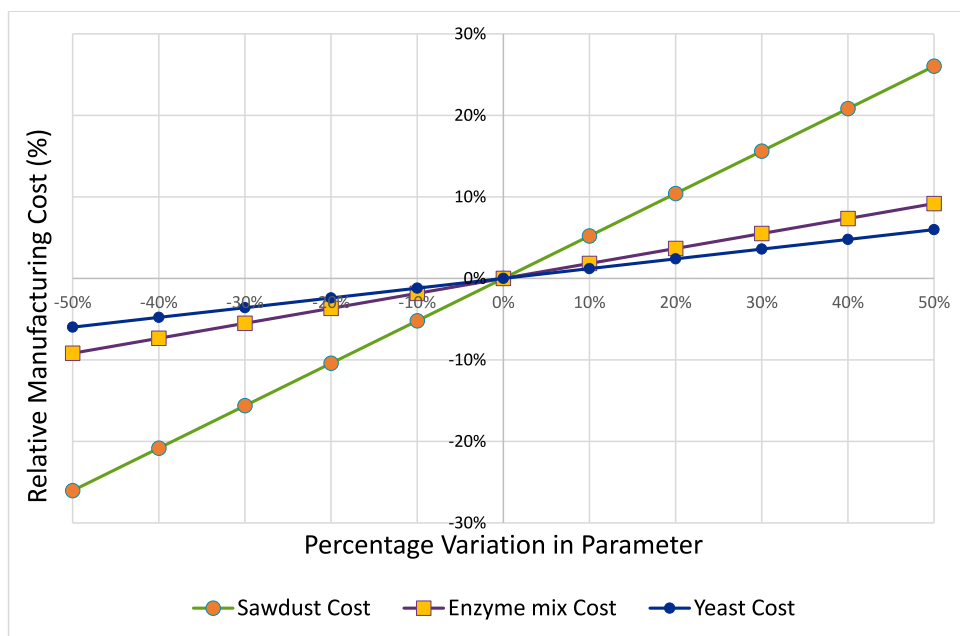


Fig. 7. Sensitivity analysis of the bioethanol manufacturing costs. The parameters included are sawdust, enzyme mix, and yeast costs.

is impossible to estimate the exact effect of these technical changes on the process economics.

The NPV of bioethanol manufacture at different discount rates is presented in Fig. 6, and Fig. 7 shows the sensitivity analysis based on sawdust, enzyme mix, and yeast prices.

The NPV is highly unfavourable: only with the lowest discount rate (2 %) does the NPV show positive values within the 25-year timespan; after 25 years, the NPV varies from c. +€100 M to -€210 M, depending on the discount rate. Of course, the overall economics depend mostly on the selling price of ethanol and the price of the raw material, which are

subject to change. Nevertheless, based on the assumptions used in this study, the operational costs compared to revenues are too high to deal with the high investment costs. As will be discussed below, the situation changes slightly when the more favourable economic figures from the pyrolysis process are added.

A sensitivity analysis performed on the raw material costs shows that the cost of the produced bioethanol depends heavily on the sawdust price: a 20 % increase in the sawdust price increases the product cost by 10 %. Enzyme-mix and yeast prices also have a high impact on the cost of the produced bioethanol.

Table 10

Material streams in the pyrolysis process. The overall yield of the process, calculated from the final product and the dry matter of the sawdust raw material, is 18.6 %. DMC = dry matter content; o.d. = oven dry.

Material	Material flow	
	[t/h]	[kt/a]
Raw material, DMC 57 %	33.5	277
Raw material, o.d.	19.0	157
Water evaporated from raw material	13.1	108
Biochar produced	7.59	62.7
Bio-oil produced, moisture content 30.5 wt%	10.9	90.1

Table 11

CAPEX breakdown (pyrolysis process). FCI = fixed capital investment.

Cost item	[€M]	[% of eq.]	[% of FCI]
Equipment (delivered)	15.3	100	22
Installation	5.3	35	8
Piping	5.3	35	8
Insulation & painting	2.3	15	3
Instrumentation & controls	5.3	35	8
Electricity	3.1	20	4
Buildings	3.1	20	4
Yard	1.5	10	2
Services	4.6	30	7
Engineering & supervision	5.3	35	8
Legal expenses	0.6	4	1
Construction & startup	4.6	30	7
Contractors	2.3	15	3
Subtotal	58.6		
Contingency	11.7	20	17
Total FCI	70	[€M]	100
Working capital	2.5	[€M]	
CAPEX	73	[€M]	

Table 12

OPEX breakdown (pyrolysis).

#	Items	unit/a	unit	[€/unit]	[€M/a]	[% of C _{OP}]
1	Raw materials	0	[t]	0	0.0	0.0
2	Propane	1000	[t]	350	0.35	3.5
3	Other utilities	2000	[t]	100	0.20	2.0
4	Electricity	62,168	[MWh]	60	3.73	37.2
5	Waste	103,358	[m ³]	2	0.21	2.1
6	Maintenance & repairs ^a				1.5	15.2
1–6	Variable cost				6.0	60.0
7	Salaries & social expenses ^b				1.2	12.0
8	Insurance ^c				0.3	3.0
9	Administration ^d				0.5	5.0
10	Sales&marketing ^d				0.5	5.0
11	R&D ^d				0.5	5.0
12	Security & healthcare ^d				0.5	5.0
13	Quality control ^d				0.5	5.0
7–13	Fixed cost				4.0	40.0
	Total operating cost, C _{OP}				10.0	

^a 10 % of equipment.

^b 20 persons.

^c 2 % of CAPEX.

^d 12 % of fixed OPEX.

The material streams of the pyrolysis process are presented in Table 10.

The determined CAPEX and OPEX for the pyrolysis process are presented in detail in Table 11 and Table 12 respectively.

The pyrolysis of the solid hydrolysis residue is technically possible, as the published literature shows (Pienihäkkinen et al., 2021). However,

the authors note that the raw material's chemical composition has an impact on the process's technical viability: a higher carbohydrate content was reported to increase both the processability of raw materials and the bio-oil yield. Because the carbohydrates are mostly dissolved from the sawdust in the bioethanol process, we suggest that the raw material has a very low carbohydrate content, which may not be an optimal chemical composition for pyrolysis feedstock. Additionally, as high temperatures are used in pyrolysis and combustion, resistant materials are required, making the equipment prices rather high. Moreover, due to extensive material flows, equipment sizes are big, which increases capital investment costs. In operating costs, the share of the electricity is more than 37 %. This is because extremely large volumes of gases need to be blown, principally air.

The pyrolysis products have a relatively high economic potential, which makes the pyrolysis economics more favourable than bioethanol production. The price expected from biochar seems to be especially attractive (€1200/t was the price used in the calculations).

The economic figures from the bioethanol and the pyrolysis processes are combined in Table 13.

The combined figures underline the unfavourable figures of bioethanol production compared to the pyrolysis process: capital investment, as well as the operational costs, are very high for bioethanol production, making the overall economic balance unfavourable.

3.3. Life cycle assessment

3.3.1. LCA result and discussion

Fig. 8 illustrates the distribution of emissions throughout the life cycle of bioethanol production. The outcomes for GWP over a 100-year timeframe, considering fossil-based sources, biogenic sources, and LULUC were 0.26, 0.002, and - 0.92 kg CO₂ eq./l bioethanol respectively. The GWP-related emissions release at various stages is intricately linked to the preparation of sawdust, the production of diverse raw materials, and transport. The primary focal point, contributing significantly to emissions, is identified as sawdust preparation, followed by sodium hydroxide, enzymes, transport, pyrolysis process, and yeast. Emissions originating in plant operations constitute a minor proportion of the overall GHG emissions from bio-ethanol production. A noteworthy aspect is the role of the byproduct, biochar, which, when recovered and combusted for heat generation, plays a substantial role in counteracting the GHG emissions that would otherwise result from energy consumption derived from external sources. The GWP-LULUC results in net sequestration are mainly due to carbon stock changes in sawdust raw material, with 79 % attributed to changes in living biomass, 18 % to soil carbon in mineral soil, and the remainder to carbon stock changes in dead organic matter and litter (approximately 8 % and 2 % respectively). Organic soils contribute small emissions instead of sequestration (i.e. around -8 % of sequestration).

The calculated range for net emissions, spanning 0.75 to 0.94 kg CO₂ eq./l bioethanol, is extrapolated from the findings detailed in the investigation conducted by Roy and Dutta, 2013. In their study, they

Table 13

Combined economic balance for the bioethanol and pyrolysis processes. The revenues and the OPEX represent annual values.

Items	Amount	Unit
Revenue from bioethanol	94	€M
Revenue from biochar	75	€M
Revenue from bio-oil	52	€M
Total revenue	221	€M
CAPEX bioethanol	405	€M
CAPEX pyrolysis	73	€M
Total CAPEX	478	€M
OPEX bioethanol	75	€M
OPEX pyrolysis	10	€M
Total OPEX	85	€M

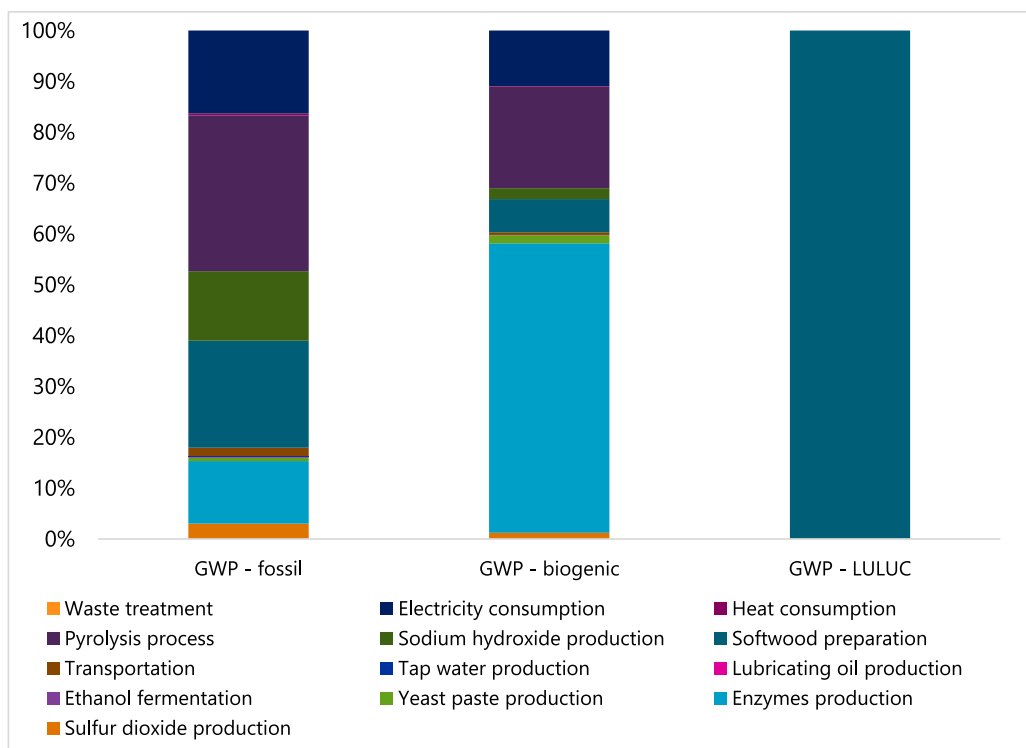


Fig. 8. Distribution of emissions throughout the life cycle of bioethanol (year 2021).

accounted for the fact that a proportion of the energy required for the bioethanol production process was offset by utilising the recovered byproduct (lignin) for heat generation. However, in the present study, the entirety of the requisite energy was considered to be supplied through the energy obtained from byproduct (stillage) combustion. Alizadeh et al. (2023) revealed that GHG emissions from wood sawdust ranged between 0.56 and 0.13 kg CO₂ eq./kg bioethanol, depending on whether the sawdust was treated or untreated. The findings of this study revealed a range of 0.4 to 0.002 kg CO₂ eq./kg bioethanol, depending on the specific impact category under consideration.

In this study, a comprehensive life cycle assessment was undertaken to scrutinise the GHG emissions associated with three distinct fuel types: petrol; E20 (20 % ethanol blend); and E85 (85 % ethanol blend). The results (Fig. 9) reveal significant variations in the carbon footprints of these fuels, considering both the production and use phases. For petrol, the total emissions amounted to 3.14 kg CO₂ eq./l, with 0.76 kg CO₂ eq./l

stemming from the production phase, and 2.38 kg CO₂ eq./l from the use phase. In contrast, E20 exhibited reduced emissions, totalling 2.55 kg CO₂ eq./l, comprising 0.64 kg CO₂ eq./l from production and 1.9 kg CO₂ eq./l from use. E85 emerged with the lowest total emissions at 0.6 kg CO₂ eq./l, attributable to 0.24 kg CO₂ eq./l from production and 0.36 kg CO₂ eq./l from the use phase. These findings underscore a discernible trend of diminishing emissions from petrol to E20 and further to E85, emphasising the potential environmental benefits associated with ethanol-blended fuels.

Compared to conventional petrol, E20 (20 % ethanol blend) and E85 (85 % ethanol blend) demonstrate reductions in fossil impacts of 18 % and 77 % respectively (ref. Fig. 9). Notably, their GWP-LULUC emissions are approximately -0.1 and - 1.09 times the fossil impacts of petrol, with E85 even resulting in net sequestration rather than emissions. These substantial potential environmental benefits are primarily attributable to the renewable nature of ethanol and the associated reduction in GHG emissions. In the case of E20 and E85, where a significant portion of the fuel is derived from renewable sources like sawdust, the overall impact on carbon neutrality in the use phase can be favourable. The carbon dioxide released during the combustion of these ethanol blends is considered part of the natural carbon cycle, as it was absorbed by the plants during their growth. This cycle contrasts with the use of fossil fuels like petrol, where burning releases carbon dioxide that has been sequestered for millions of years, contributing to a net increase in atmospheric carbon dioxide levels. These findings underscore the significant role carbon stock dynamics play in shaping the environmental footprint of bioethanol and emphasise the potential for emissions

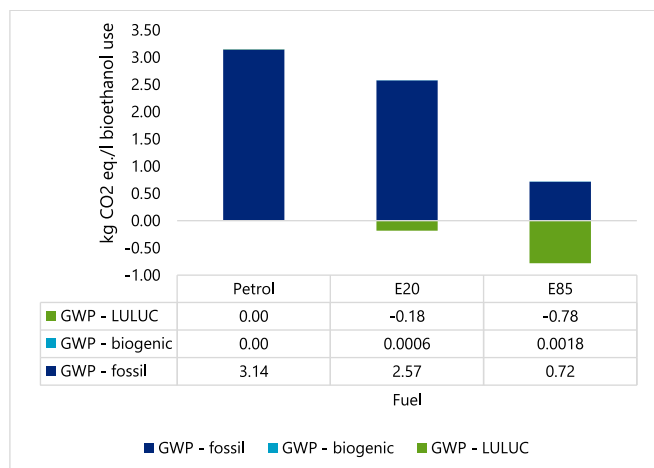


Fig. 9. Life cycle GHG emissions from different fuels (2021).

Table 14
Parameters used in the sensitivity analysis.

Scenario	Parameter
Baseline scenario SA 1	saw dust wood chips
Baseline scenario SA 2	42 % of the GWP impact allocated to bioethanol production
	99.7 % of the GWP impact allocated to bioethanol production.

reduction offered by bioethanol as a sustainable alternative to traditional fossil fuels.

3.3.2. Sensitivity analysis

Sensitivity analysis serves as a critical methodological tool in environmental research, playing a pivotal role in enhancing the reliability, comprehensiveness, and applicability of study findings. In this study, two sensitivity analyses were conducted based on raw material change (SA 1) and allocation factor change (SA 2) (please refer to Table 14.)

In the baseline scenario, sawdust was strategically chosen as the elementary material for bioethanol production. However, to acknowledge the diverse range of woody biomass available for this process, it is necessary to explore alternative sources. This led to a sensitivity analysis focusing on the environmental impact of producing bioethanol from woodchips, which allowed meaningful comparisons with the baseline scenario. Bioethanol, a key player in sustainable energy, can be derived from various types of woody biomass. The sensitivity analysis addressed this variability, providing a nuanced understanding of the environmental implications associated with different feedstocks.

Specifically comparing the outcomes of utilising woodchips or sawdust reveals that bioethanol production from woodchips exhibited a remarkable environmental advantage over its counterpart from sawdust. The findings (refer to Fig. 10) revealed a substantial reduction of approximately 20 % in emissions when bioethanol was produced from woodchips compared to sawdust. The primary driver behind this significant difference can be attributed to the distinct characteristics of the ethanol production processes from these two woody biomass sources. Notably, the sawdust production process was identified as inherently more emission-intensive than its counterpart from woodchips.

A critical aspect of our study involved revisiting the allocation of emissions within the bioethanol production process. In the baseline scenario, ethanol production accounted for 42 % of the total emissions attributed to the process. The final ethanol product typically achieves a purity of 99.7 %. In recognising the importance of precision in environmental impact assessments, particularly for processes like ethanol production where no byproducts are generated, this sensitivity analysis explores the implications of allocating emissions based on the actual ethanol content (99.7 %) achieved. The findings indicate that altering the allocation factor resulted in a significant change in the overall environmental impact. For example, the GWP 100 (fossil) exhibited maximum variation. The initial value of 0.26 kg CO₂ eq./l bioethanol in the baseline scenario experienced a marginal increase to 0.62 kg CO₂ eq./l bioethanol (see Fig. 11). This subtle shift in the GWP 100 fossil suggests that the allocation of emissions, even when refined to account for the ethanol content, had a significant impact on the broader environmental footprint of bioethanol production.

3.3.3. GWP-LULUC – Temporal and regional variation

Fig. 12 presents the land use and land-use-change-related GWP impacts (GWP-LULUC) for bioethanol production in the European Union

(EU) across different years. These emissions are shown for different years, and between mineral and organic soils specifically for 2021. These findings underscore the significance of carbon stock changes in LULUC, which significantly affect the greenhouse gas impacts across the bioethanol life cycle.

Overall, the GWP-LULUC sequestration resulting from carbon stock changes outweighs the fossil fuel-related impacts associated with bioethanol production, and the extent of this sequestration potential varies in different years and soil types. This sequestration results from several trends in EU forests: the removal and natural loss have been lower than the gross increment; the forest area has been increasing; and the forests grow more densely and quickly than before (Forest Europe, 2020, Anttila and Verkerk, 2022). However, in some regions of the EU, the peak in net annual increment seems to have been passed (Forest Europe, 2020). The emission and sequestration due to the changes in carbon stock must be accounted for in LCA in accordance with the ISO (2018) standard. Here, we have calculated it for the first time by applying national inventory report (NIR) data to LCA, ensuring the results' comparability and reliability. Understanding the dynamics of carbon stock changes will assist in informed decision making in achieving reduced GWP impact targets.

Carbon sequestration is directly influenced by the harvesting level, that is, reduced carbon stock with increased harvesting rates. The sequestration potential therefore fluctuates with living biomass levels, varying from 4.5 times the fossil impacts of bioethanol production in 2017 to 3.3 times in 2021. This shift results from declining living biomass, reflected in a decreased carbon stock increase, from 0.51 tC/ha in 2017 to 0.38 tC/ha in 2021. Wood removal has also risen, reaching 579 million m³ in 2021, compared to 528 million m³ per tonne in 2017.

Additionally, soil type significantly impacts GWP-LULUC emissions and removals. For example, in 2021, mineral soil exhibits 3.6 times higher sequestration potential than fossil impacts from bioethanol, while organic soil shows emissions 0.2 times higher than total fossil impacts. This mainly occurs due to higher CO₂ emissions and methane emissions originating in organic soils.

These LULUC-related sequestrations are influenced across EU countries, ranging from approximately -0.6 times the fossil impacts for Estonia to roughly 14 times the fossil impacts for Luxembourg and Spain (please refer to Fig. 13; the data are also presented in the supplementary materials Table S1.). Estonia experiences a net decrease in living biomass, and a significant portion of its forest land is organic soil, accounting for around 25 % of its total forest land. On the other hand, Spain does not have organic soil. Luxembourg exhibits one of the highest increases in living biomass (1.77 tC/ha) in the EU. However, its small forest land area leads to fluctuations over the years. Latvia and Finland show relatively lower sequestration potential, at approximately 0.3 and 0.5 times the fossil impacts respectively. For example, the increase in living biomass in Finland has decreased from 0.30 tC/ha in 2017 to 0.18 tC/ha in 2021, while the harvesting of wood carbon has increased from 0.74 tC/ha in 2017 to about 0.78 tC/ha in 2021. The age structure also

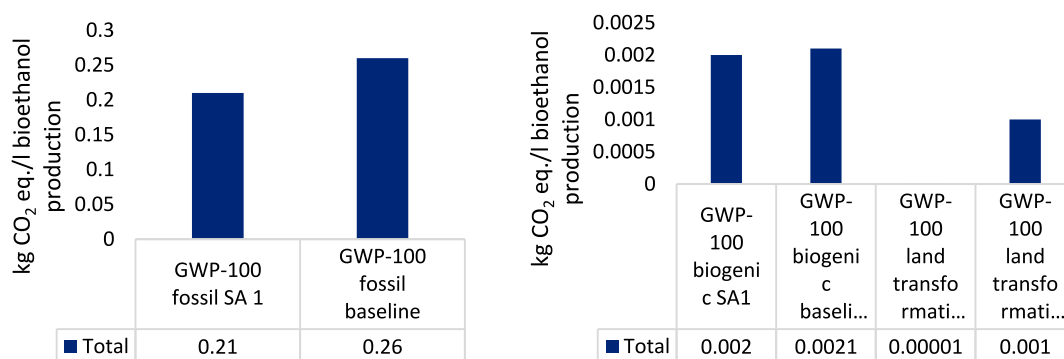


Fig. 10. GWP results of baseline and SA 1 scenarios.

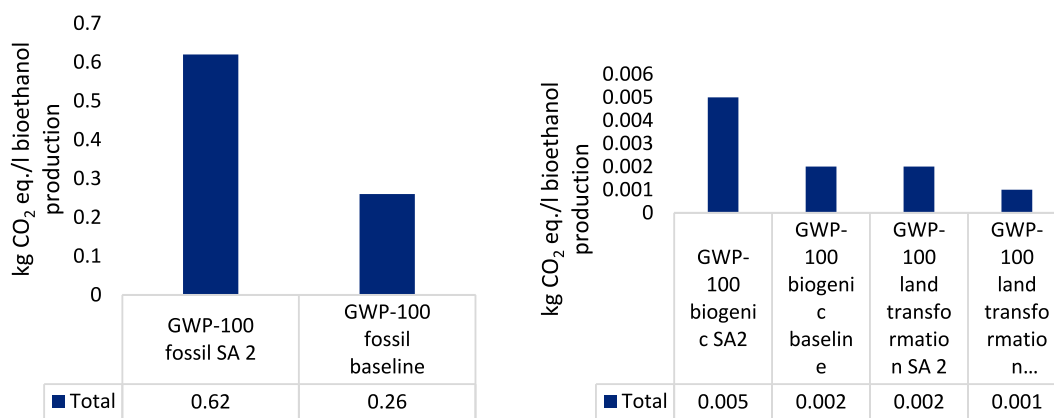


Fig. 11. Life cycle GHG emission results of baseline and SA 2 scenarios.

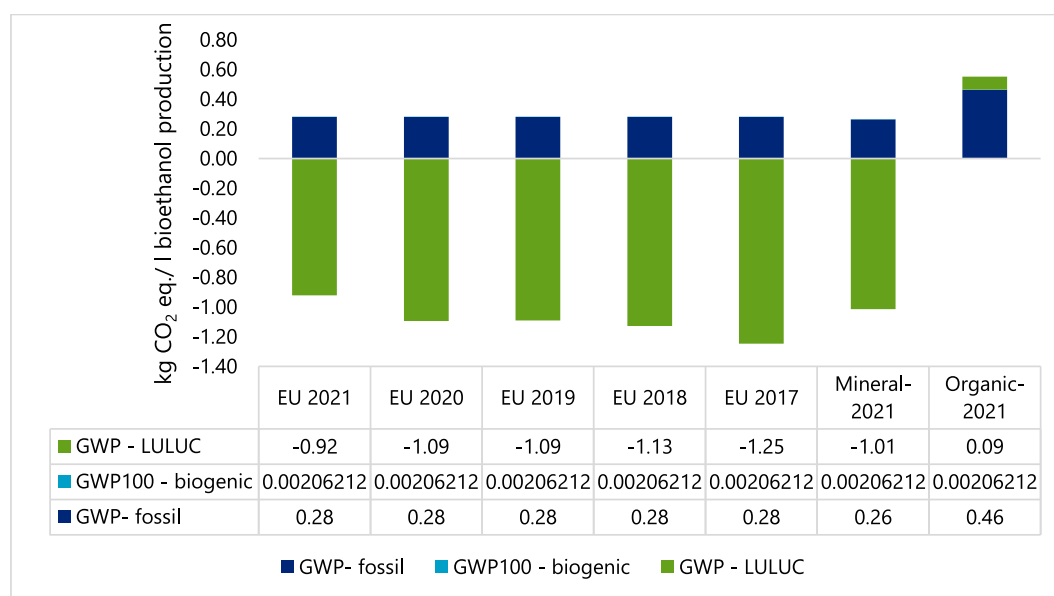


Fig. 12. Life cycle GHG emissions, including the LULUC for bioethanol production in the EU across different years.

affects tree growth in Finland, as most of the forests are more than 60 years old and are therefore now starting to exceed their best growth stage (Metsä, 2024; Nöjd et al., 2021; Pan et al., 2024). This decrease has reduced the sequestration potential of forest products in Finland – for example, bioethanol. Overall, forest-based bioethanol’s sequestration potential demonstrates regional and temporal fluctuations. Sequestration increases with rising living biomass but decreases with intensified harvesting and a higher presence of organic soils.

4. Conclusion and recommendation

In this study, we have applied an integrated assessment approach to evaluate the sustainability of sawdust-based bioethanol production in the European Union, including an estimate of the potential of sawdust, a TEA analysis, and GWP impacts. Overall, based on the assumptions made in this study, it was concluded that sawdust-based bioethanol demonstrated the potential to replace some fossil fuels, offering technical feasibility and considerable environmental benefits. However, it is not economically feasible and is highly influenced by policy changes and competition between different sectors. Therefore, based on our findings, the high expectations in the EU for lignocellulose-based biofuels are not very realistic.

The average annual supply potential of conifer sawdust in the EU was

found to be around 10.7 million dry tonnes during 2013–2022, corresponding to around 1.3 million tonnes of bioethanol. Bioethanol production based on average annual sawdust potential could have replaced 0.5 % of total fuel consumption in the EU in 2021, provided that all the sawdust was used for this purpose. The result indicates that sawdust-based ethanol can only play a minor role in decarbonising of the transport sector in the EU.

The TEA carried out in this project suggests that with the assumptions used, the combined production of bioethanol and pyrolysis products is not economically feasible due to the high capital cost of the investments in the bioethanol process, whereas the economic feasibility of the pyrolysis processes seems somewhat better. It is therefore relevant to ask if it was economically more favourable to pyrolyse sawdust directly. A major obstacle to the economic production of liquid biofuels from sawdust is the current high price level of this raw material. Other side-streams from the forest products industry or agriculture, such as wood bark or cereal straws, should therefore be considered as raw materials. However, as the chemical composition of these feedstocks differs greatly from sawdust, the results presented here cannot be used to predict the potential to process other lignocellulosic biomasses.

In comparing bioethanol to traditional fuels, our investigation extended to petrol, E20 (20 % ethanol blend), and E85 (85 % ethanol blend). The results indicate a notable trend of reducing emissions,

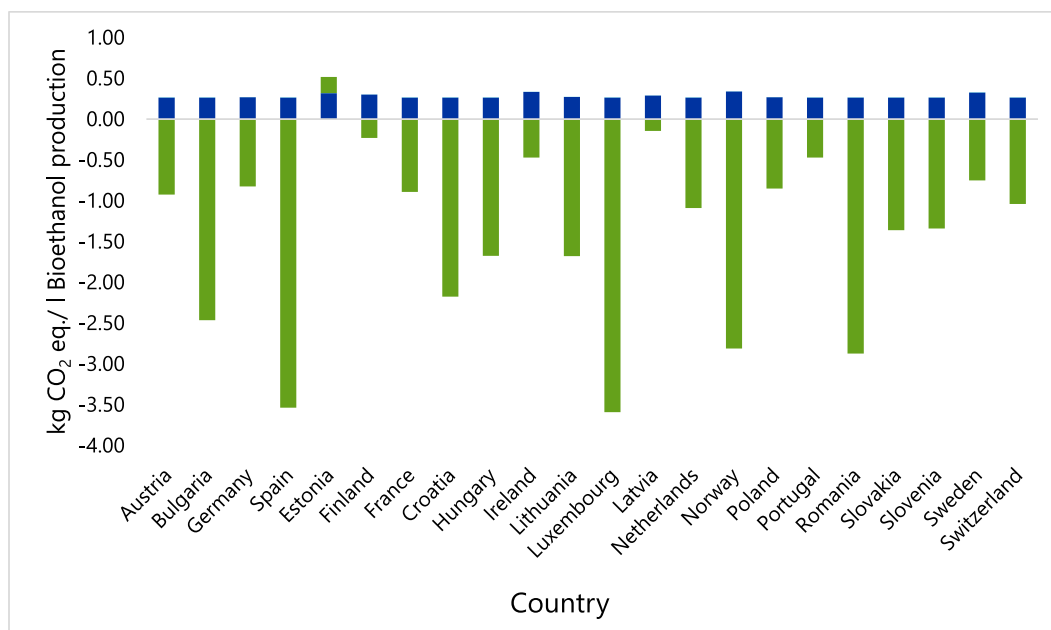


Fig. 13. Life cycle GHG emissions, including the LULUC for bioethanol production, in different EU countries and Switzerland (2021). Colour codes same as in Fig. 12.

highlighting the potential environmental benefits in terms of GWP associated with ethanol-blended fuels. Compared to petrol, E20 and E85 fuels show reductions in GWP of 18 % and 78 % respectively. Fuels derived from renewable sources like sawdust therefore demonstrate enhanced potential for carbon neutrality during the use phase, a stark contrast with the carbon release associated with fossil fuels. Nevertheless, the study scrutinised various stages of bioethanol production, revealing that sawdust preparation emerged as a primary point in significantly impacting emissions, followed by enzyme, SO₂, yeast, and tap water production. It is noteworthy that emissions from plant operations and waste treatment constituted a minor proportion, emphasising the importance of targeted interventions.

The inclusion of GWP-LULUC emissions in the assessment of bio-based products such as forest bioethanol is important in determining their environmental sustainability. For example, considering GWP-LULUC emissions from forest bioethanol production in the EU reveals a net sequestration effect, due primarily to the increasing carbon storage in forests. By including these emissions in the life cycle greenhouse gas assessments for 2021, the GWP-LULUC emissions for E20 and E85 fuels were therefore calculated at around -0.1 and -109 times the fossil impacts respectively. However, the potential for GWP-LULUC-related sequestration is variable and contingent on factors such as the production year, country of origin, or soil type where the forest raw materials are sourced for bioethanol production. These variables could lead to net emissions instead of sequestration.

CRedit author statement

All authors have made equal contributions, and their names are listed in alphabetical order.

Author contribution

Hafiz Usman Ghani, Kyösti Ruuttunen, Md. Musharof Hussain Khan, and Perttu Anttila conducted the writing and modelling. Hannu Ilvesniemi and Ilkka Leinonen provided supervision for the project. Pekka Oinas acted as process simulation expert.

Declaration of competing interest

The authors declare no competing financial interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eiar.2025.108035>.

Data availability

Data will be made available on request.

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