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Klimatpåverkan av några alternativa användningar av den ligninrika biprodukten från produktionen av jästolja

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The overarching vision of the programme Mistra Food Futures is to create a science-based platform to enable transformation of the Swedish food system into one that is sustainable (in all three dimensions: environmental, economic and social), resilient and delivers healthy diets. By taking a holistic perspective and addressing issues related to agriculture and food production, as well as processing, consumption and retail, Mistra Food Futures aims to play a key role in initiating an evidence based sustainability (including environmental, economic and social dimensions) and resilience transformation of the Swedish food system. This report is a part of Mistra Food Future's work to identify agricultural systems with potential to make agriculture net-zero, one of the central issues within Mistra Food Futures.

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Abstract

Yeast oil can be produced from lignocellulosic materials such as straw and forest residues by oleaginous yeasts. In the conversion process, cellulose and hemicellulose are consumed to produce the oil, leaving the lignin fraction of the biomass. Some of this fraction is used for internal energy production in the biorefinery, but the remainder is a byproduct from the process. This study explored the climate impact of alternative uses of the lignin-rich byproduct from a lignocellulosic biorefinery producing biodiesel from straw using oleaginous yeast. Three alternative uses were considered: asphalt amendment (replacing bitumen), pyrolysis oil and soil amendment. The climate impact of the biorefinery system included straw harvesting and related soil organic carbon changes, straw transport, and biorefinery processing, including inputs and energy use. The climate impact was analysed using a time-dependent climate model and the commonly used global warming potential metric. The results showed that straw harvesting and use in the biorefinery for production of biofuels and other products, such as asphalt ingredients, was beneficial for the overall climate impact compared with a fossil reference system, even when soil organic carbon losses due to straw harvesting were included. In a climate impact perspective, the most beneficial use of surplus lignin was as asphalt amendment, especially if the asphalt served as a carbon sink.

Keywords: biorefinery, climate impact, lignocellulosic biorefinery, biodiesel, soil organic carbon, bitumen

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1. Introduction

Lignin is an abundant material found in woody biomass and other types of biomass such as agricultural residues. Because of its abundance and complex properties (many potential uses), lignin has been the focus of significant research in recent years (Moretti *et al.*, 2021; Wenger *et al.*, 2020; Glasser, 2019). Lignin is a byproduct from pulp and paper production, but also from biochemical biorefineries. The most common use of lignin at present is production of energy via combustion (Moretti *et al.*, 2021), often for internal use at the pulp and paper mill or the biorefinery. However, in many cases there is surplus lignin. Further, it may be possible to use other energy sources for internal biorefinery energy demand, and thereby make more lignin available for other uses such as production of biofuels or biochemicals.

Extraction of lipids from lignocellulosic biomass using different strains of oleaginous yeast enables production of food, feed and high-value energy carriers from lignocellulosic materials (Passoth, 2017). When harvested sustainably, lignocellulosic materials such as straw used in this way can be valuable byproducts from agriculture, enabling higher production of feed, food and energy from a certain area of land. The climate impact of using oleaginous yeast to produce biofuels (Karlsson *et al.*, 2017; Parsons *et al.*, 2017) and fish feed (Sigtryggsson et al., manuscript) has been studied. In previous climate impact assessments, the lignin-rich residue from the fermentation process has often been assumed to be used as an internal energy supply in the biorefinery. This study explored the climate impact of some alternative uses of the lignin-rich byproduct. The focus of much previous work has been on lignin residues from the pulp and paper industry, but with increasing production of fuels and chemicals from lignocellulosic materials the availability of lignin from biochemical conversion of *e.g*. agricultural residues is expected to increase (Xie *et al.*, 2016). In principle, there are many applications for lignin (Moretti *et al.*, 2021; Glasser, 2019), of which three were considered in the present study.

1.1. Aim

The aim of this study was to explore the climate impact of alternative uses of lignin-rich byproducts from a lignocellulosic biorefinery producing biodiesel from straw using oleaginous yeast. The following lignin applications were compared with combustion and electricity production from the lignin-rich byproduct on-site:

- Ingredient in asphalt production, replacing bitumen
- Pyrolysis oil
- Returned to the soil, with soil organic carbon modelled over 100 years.

2. Method

Biorefinery description

The type of biorefinery analysed in this study was a biochemical conversion plant that primarily uses the sugars from cellulose and hemicellulose in straw to produce oleaginous yeast biomass with around 50% lipid content (Figure 1). The principles behind the biorefinery concept are described in detail in Karlsson *et al.* (2016) and Karlsson *et al.* (2017). To summarise the process, the straw is first pre-treated using steam explosion, followed by enzymatic hydrolysis to free the sugars for use in fermentation. During fermentation, the sugars are converted to lipids by an oleaginous yeast (*Lipomyces starkeyi*). The lipids are extracted and used for producing biodiesel. The remaining yeast biomass is used to produce biogas that can be utilised as transportation fuel. In climate analyses of the process, the lignin which remains after hydrolysis is often assumed to be used to meet the internal energy demand of the biorefinery (Karlsson *et al.*, 2016). However, depending on the biorefinery set-up and the extent to which electricity is bought or produced from renewable sources on-site, different amounts of lignin can be available for other uses. In the study by Karlsson *et al.* (2017), this is exemplified by an *External El prod s*cenario with natural gas used to generate process electricity. In the present study, we considered renewable electricity, exemplified by wind power (50%) and solar power (50%), to represent possible on-site electricity production.

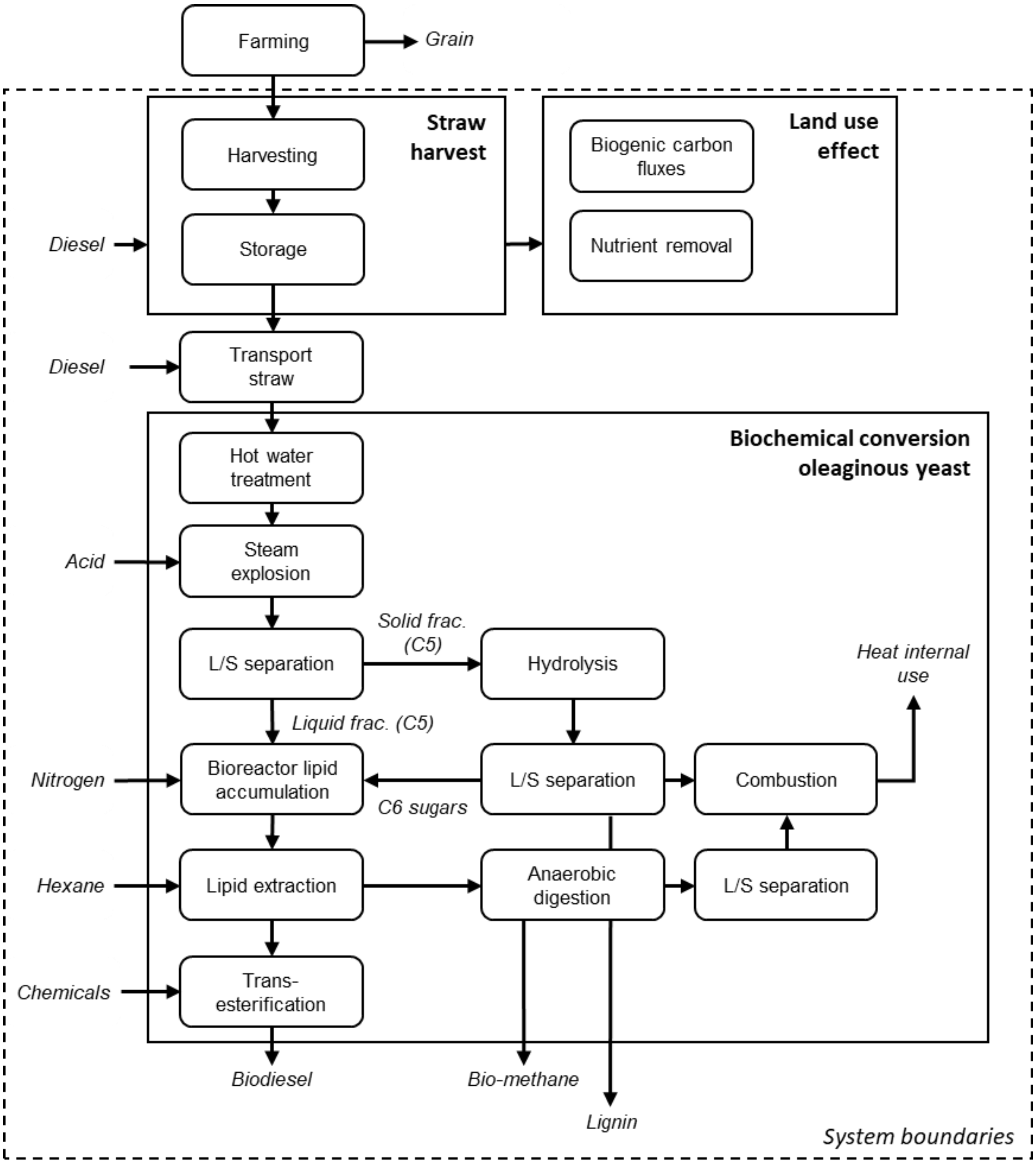

Figure 1. Biochemical conversion of straw to lipids using oleaginous yeast. Depending on internal energy demand and alternative energy sources used, different amounts of lignin can be available for other applications.

2.1. Scenario description

The following scenarios were considered (Figure 2):

1. *All internal heat produced from the lignin* (surplus lignin sold):
   a) Lignin as asphalt amendment
   b) Lignin for pyrolysis oil
   c) Lignin as soil amendment

The difference between systems 1a, 1b and 1c is end-use of the lignin byproduct.

2. *All internal energy produced from the lignin*, where lignin is combusted to cover all heat and electricity demand of the biorefinery and surplus lignin is used as a soil amendment.

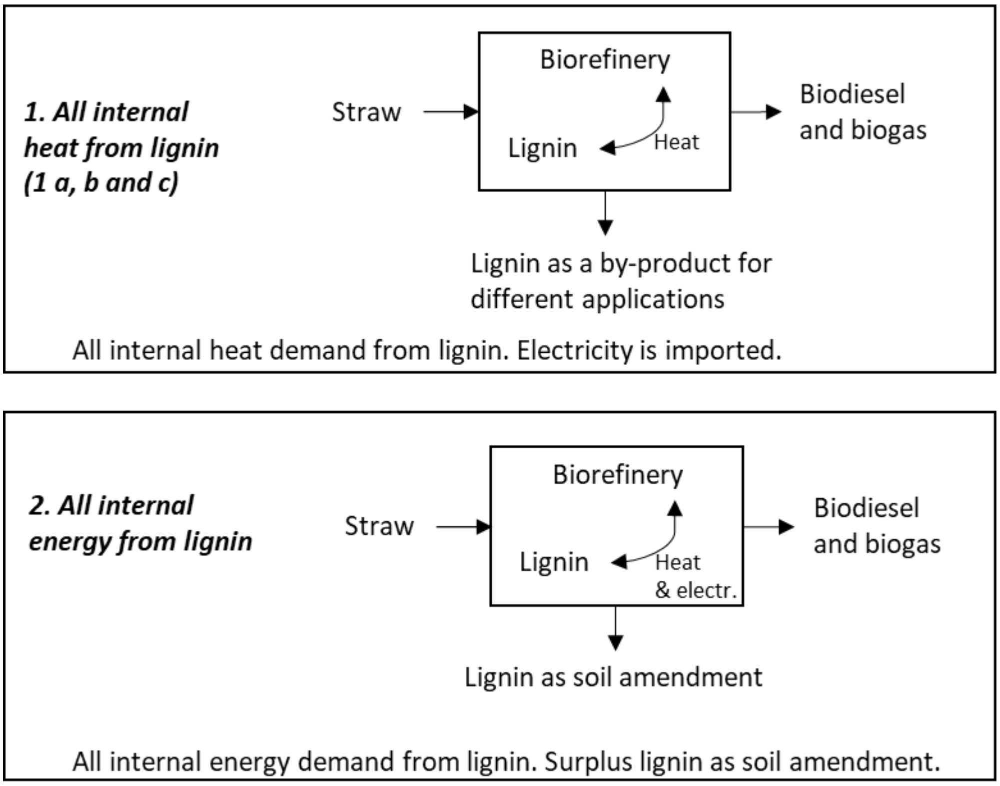

Figure 2. Scenarios considered in the present study.

2.1.1. Lignin applications

For the surplus lignin in scenario 1a, 1b and 1c, three different applications were assessed: asphalt amendment (replacing the fossil product bitumen to 50%), production of pyrolysis oil, and soil amendment. These are further explained below.

Bitumen in asphalt blends

Bitumen is a fossil product that is incorporated to a level of around 5% in asphalt (Tokede *et al.*, 2020). Partial replacement of bitumen with different lignin products has been studied previously from a technical perspective (*e.g*. (Pasandín *et al.*, 2022; Pérez *et al.*, 2019) and an environmental perspective (Tokede *et al.*, 2020; Khandelwal, 2019; Balaguera *et al.*, 2018). Replacement rate varies, but it has been suggested that up to 50% of the fossil component could be replaced with lignin (Khandelwal, 2019). The replacement rate was not important for the results in the present study, but it determines the market volume and is important for the final environmental impact of the asphalt. Since our focus was on the replacement potential of the lignin-rich byproduct and since the market can be very large (global asphalt production), we deemed it relevant to assume that 1 kg lignin replaces 1 kg bitumen. However, it is important to bear in mind that the replacement rate is important for the potential of the technology to reduce the overall environmental impact from asphalt production.

The assumptions made for bitumen replacement were that the lignin is dried to around 7% moisture content and in that form replaces bitumen 1:1 (Khandelwal, 2019). In one scenario, all carbon in the lignin was assumed to be stored in the asphalt for 17 years (estimate from Svenson (2013)), contributing to *negative emissions*. However, the potential to store biogenic carbon in asphalt is uncertain for several reasons, for example the estimated lifetime of the road can vary depending on traffic load, type of road *etc*. and the fate of carbon in the bitumen replacement product, *i.e*. how long it is stored in the asphalt, since the asphalt may degrade over time. For the calculations, it was assumed that 60% of the lignin byproduct consisted of carbon (Glasser, 1985) and that all carbon ended up in the bitumen replacement product. Further, it was assumed that the carbon is released to the atmosphere when the road is resurfaced.

Pyrolysis oil

We assumed direct pyrolysis of the lignin to pyrolysis oil and further processing to synthetic biofuels, using process details taken from Obydenkova *et al.* (2017). According to that study, the yield of the process is 0.33 kg pyrolysis oil (27.9 MJ/kg oil) per kg dry lignin. Biochar and pro-gas generated during pyrolysis are used to dry the lignin and to generate heat for pyrolysis. Electricity is consumed to a rate of 0.068 kWh per kg dry lignin in the pyrolysis step and 0.076 kWh per kg dry lignin for hydrotreatment (further processing to biofuels), while hydrogen is consumed to a rate of 1.44 MJ per kg dry lignin (Obydenkova *et al.*, 2017). The pyrolysis oil is assumed to be further processed to liquid biofuels that can replace petrol or diesel and biofuel yield is set at 42% (Obydenkova *et al.*, 2017). A limitation of that study is that it does not consider the actual properties of lignin from second-generation plants, a limitation that also applied in the present study.

Soil amendment

Soil organic carbon effects of returning the lignin-rich byproduct to the soil were based on the *No Excess El* scenario (Karlsson *et al.*, 2017), where it was modelled using the Introductory Carbon Balance Model (ICBM), a soil carbon model for agricultural soils (Andrén & Kätterer, 1997).

2.2. Process (biorefinery) modelling

The biorefinery plant was modelled using the process model software Aspen Plus^{TM}. Full details of simulations, assumptions on biorefinery inputs and performance can be found in Karlsson *et al.* (2016) and Karlsson *et al.* (2017).

Lignin content in the biomass was assumed to be 26.5% (Linde *et al.*, 2008). As mentioned, the lignin used as asphalt amendment was assumed to be dried to 7% moisture content (Khandelwal, 2019). Energy use for drying the lignin was assumed to be 0.89 kWh per kg water (Rinke, 2013), and this energy was assumed to be produced by combustion of part of the lignin. It was estimated that 0.18 kg lignin was required to dry 1 kg wet lignin (60% moisture content) to 7% moisture content, a calculation based on a heating value for lignin of 24.4 MJ/kg (Domingos *et al.*, 2020). In the biorefinery, all heat was assumed to be generated from combusting lignin, leaving 0.17 kg lignin per kg dry biomass (Karlsson *et al.*, 2017). On including the heat requirement for drying the lignin, approximately 0.14 kg dry lignin was produced per kg of straw dry matter (DM) processed.

For use of the lignin-rich byproduct as soil amendment, no drying was assumed.

2.3. Soil organic carbon modelling

Soil organic carbon changes were modelled using the ICBM (Andrén & Kätterer, 1997). Through straw harvesting, less organic material is added to the soil, thereby affecting the soil organic carbon balance. The ICBM is a two-compartment (old and young carbon pools in the soil) process model based on first-order kinetics that can be used to calculate SOC changes in the top 25 cm of agricultural soil. We applied the same parameter values as in Karlsson et al. (2017), with different humidification rate for above- and below-ground crop residues (Kätterer et al., 2011). The humidification rate of the lignin residue from the biorefinery was estimated from the humidification rate of peat (Kätterer et al., 2011).

2.4. Reference systems

The fossil reference system represented equivalent products to those produced in the biorefinery, and therefor slightly differ for the different scenarios. Table 1 presents the fossil reference products used and the source of the data on emissions of greenhouse gases (life cycle inventory (LCI) data).

Table 1. Reference products for the biorefinery products and source of life cycle inventory (LCI) data

BIOREFINERY PRODUCT	REFERENCE PRODUCT	SOURCE OF LCI DATA
BIODIESEL	Fossil diesel	Gode *et al.* (2011)
BIOGAS	Petrol	Gode *et al.* (2011)
ASPHALT AMENDMENT	Fossil bitumen	Ecoinvent version 3.8 (2021)

2.5. Climate impact assessment

2.5.1. Methodological choices and system boundaries

Climate impact was assessed in a life cycle perspective and based on the functional unit 1 kg DM straw.

System boundaries are illustrated in Figure 1. The study included straw harvesting and transport to the biorefinery, soil organic carbon changes and nitrogen removal due to straw harvesting, biorefinery inputs and substitution effects from the products biodiesel and biogas, which were assumed to replace fossil diesel and petrol, respectively.

2.5.2. Climate impact metrics

Since the studied system involved soil organic carbon changes due to straw harvesting and these changes vary over time, we used two different climate impact metrics: i) Absolute Global Temperature change Potential (AGTP), also referred to as temperature response, since when assessing the climate impact of a system where emissions (and uptake) vary from year to year, it can be an advantage to use a metric that captures the timing of emissions and their impact over time. The method applied here is further described in (Ericsson *et al.*, 2013). ii) Global Warming Potential with a 100-year perspective (GWP_{100}), with characterisation factors for climate impact including climate-carbon feedback from IPCC (Forster et al., 2021). GWP is the most common climate metric used in LCA and is valuable for comparison with previous studies. However, it has the disadvantage of overlooking the timing of GHG fluxes. Therefore, it is advisable to use a second climate metric, *e.g.* AGTP, which can display more information (Levasseur *et al.*, 2016).

3. Results

3.1. Biorefinery performance

Table 1 shows production in all scenarios. Scenario 1b (pyrolysis oil) had higher production of biofuels, since the pyrolysis oil from the lignin product was used to produce biofuels. The pyrolysis process and hydrotreatment of the pyrolysis oil are the reasons why scenario 1b had higher electricity use. Lignin production was lower in scenario 1a (asphalt amendment), since part of the lignin was assumed to be used to dry the lignin. In scenario 1b, the pyrolysis products (biochar and syngas) were assumed to be used to dry the lignin, while in scenario 1c (soil amendment) the lignin was assumed not to be dried (Table 2). The lignin returned to soil is also shown in Table 1. The amount was higher for scenario 1c, where internal electricity needed for the biorefinery was assumed to be supplied as renewable electricity. In scenario 2, the electricity was produced from the lignin and the surplus (0.03 kg per kg straw) was assumed to be returned to the soil.

Table 2. Production of biofuels, biogas, electricity and lignin from 1 kg DM straw. A minus sign for electricity indicates consumption.

	BIOFUELS	BIOGAS	ELECTRICITY	LIGNIN	LIGNIN RETURNED TO SOIL
1A	4.02 MJ	3.05 MJ	-1.77 MJ	0.14 kg	0 kg
1B	4.86 MJ	3.05 MJ	-1.86 MJ	0.17 kg	0 kg
1C	4.02 MJ	3.05 MJ	-1.77 MJ	0.17 kg	0.17 kg
2	4.02 MJ	3.05 MJ	-	0.03 kg	0.03 kg

3.2. Climate impact

3.2.1. Temperature response

Figure 3 shows climate impact as the temperature response (AGTP) for all four scenarios per kg DM treated straw. The reference system, representing a fossil system with equivalent products, clearly had a higher climate impact than the biorefinery system for all scenarios analysed. The reference system for scenario 1a had the highest climate impact, because fossil bitumen production is associated with a relatively high climate impact. The SOC content varied due to the different amounts of lignin returned to the soil (Table 1), with scenario 1c (lignin as soil amendment) having the lowest impact on SOC levels. In all scenarios, it can also be seen that the effect of SOC changes declined slightly over time. Process emissions (solid grey lines) for the four scenarios were very similar. The highest process emissions were found for scenario 1b (pyrolysis oil), due to inputs of *e.g.* hydrogen in production of biofuel from pyrolysis oil.

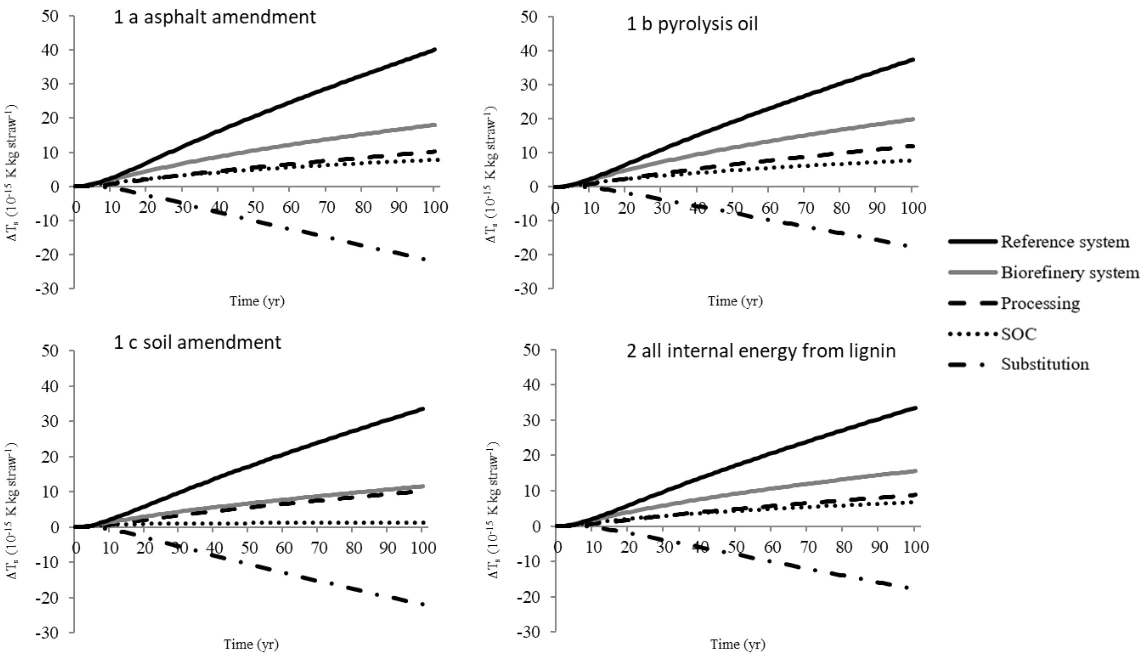

Figure 3. Temperature response in all scenarios relative to the fossil reference system, soil organic carbon (SOC) changes due to straw removal, process inputs and total climate impacts from the biorefinery system (processing plus SOC).

Substitution potential was used to assess the climate gain from the biorefinery system compared with the reference system. The highest substitution potential was found for scenario 1a (asphalt amendment) without considering carbon storage effects in asphalt and 1c (soil amendment). Scenario 1a had high substitution potential mainly due to high emissions in the reference system. Scenario 1c had high substitution potential due to relatively low impact from the biorefinery system as a whole (lower process emissions and lower SOC effects), resulting in overall higher substitution potential although the reference system did not have a high impact compared with the other scenarios.

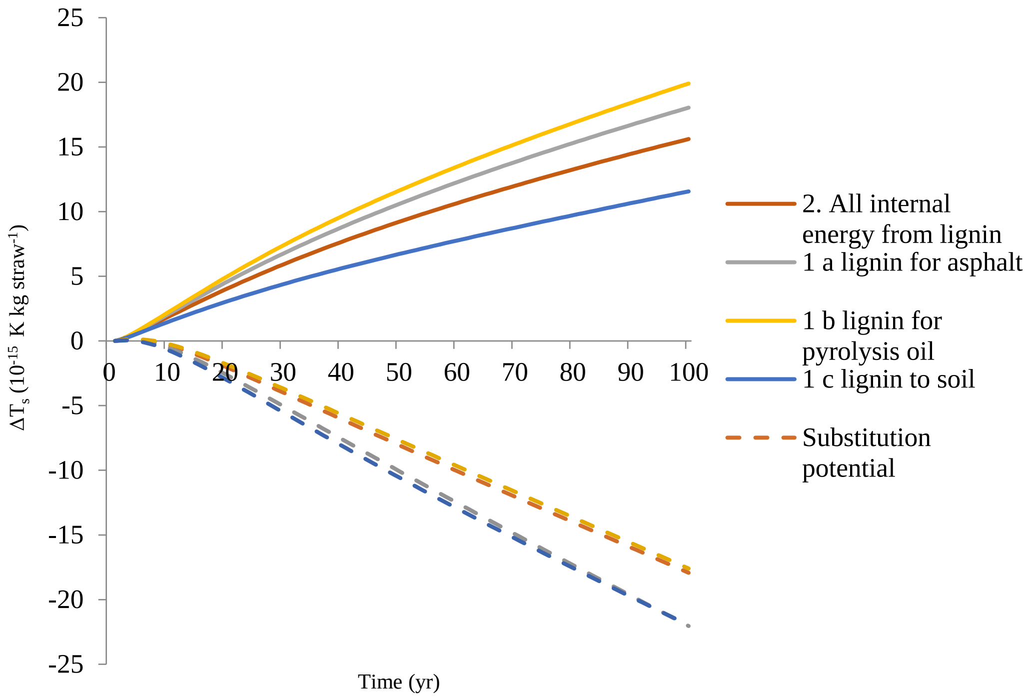

Figure 4. Comparison of temperature response for all four scenarios. Solid lines represent the climate impact from the biorefinery system (process emissions plus soil organic carbon (SOC) losses due to straw harvesting). Dotted lines represent substitution potential (process emissions plus SOC losses minus the reference system).

Asphalt carbon storage

In relation to scenario 1a, the climate impact of the asphalt serving as a biogenic carbon sink was estimated, since the biogenic carbon in the lignin is retained for some time in the asphalt product. Road lifetime was taken to be 17 years, after which the carbon was assumed to be released into the atmosphere in the form of carbon dioxide (CO2). This gave a higher temperature reduction potential in the beginning of the period in this scenario and a lower effect after 17 years (Figure 5). After 17 years the net effect became zero, since the carbon from the old road was assumed to be released when the road surface was replaced. Storage of biogenic carbon in the road partly compensated for the SOC losses due to straw harvesting (Figure 5). When storage of biogenic carbon was included, scenario 1a performed joint best (with 1c) of all scenarios with respect to substitution potential over 100 years (see Figure 4).

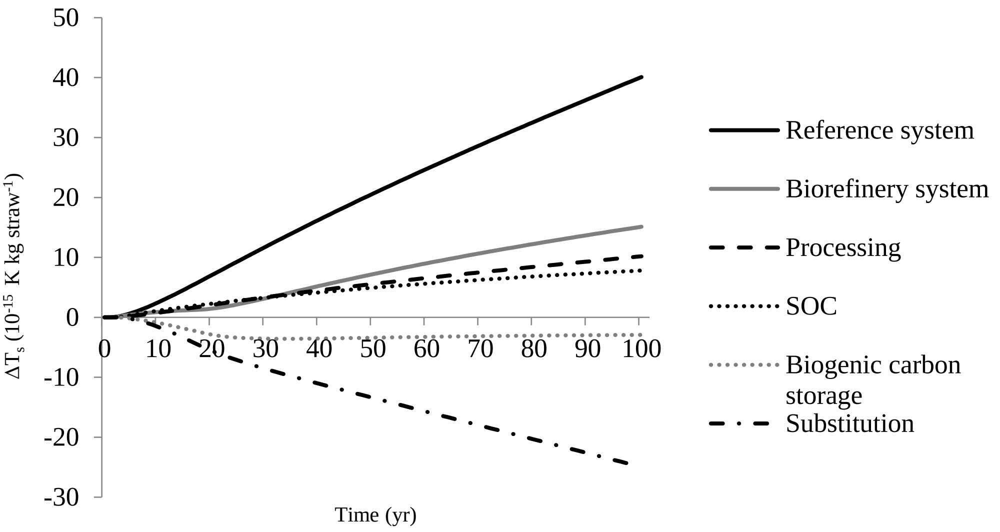

Figure 5. Temperature response in scenario 1a (asphalt amendment) when negative emissions from biogenic carbon storage in road asphalt were included.

3.2.2. Global warming potential

The climate impact of the four scenarios, expressed as GWP, is shown in Figure 6. As can be seen, SOC and biorefinery inputs (such as nitrogen for yeast growth and enzymes for hydrolysis) had the largest impact. In the diagram, 'straw harvesting' represents diesel use for harvesting, 'transport' is transport of the straw to the biorefinery and 'methane slip' is due to the biogas process that digests the yeast biomass after lipid extraction. All of these biorefinery inputs are also included in Figures 4 and 5, there called 'Biorefinery system'.

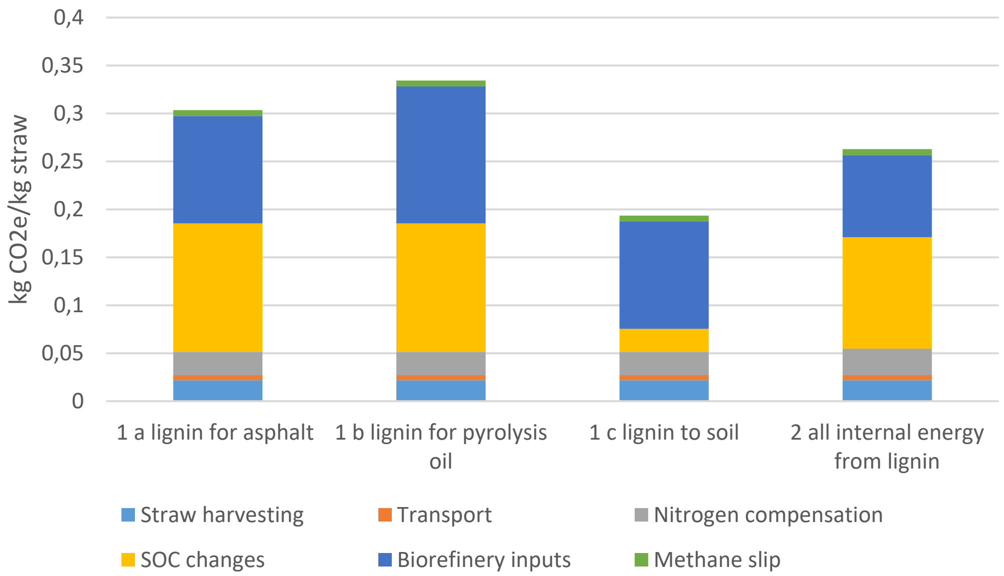

Figure 6. Climate impact (expressed in GWP100) for 1 kg DM straw processed in the biorefinery. Soil organic carbon (SOC) changes are calculated as average change due to straw removal over 100 years.

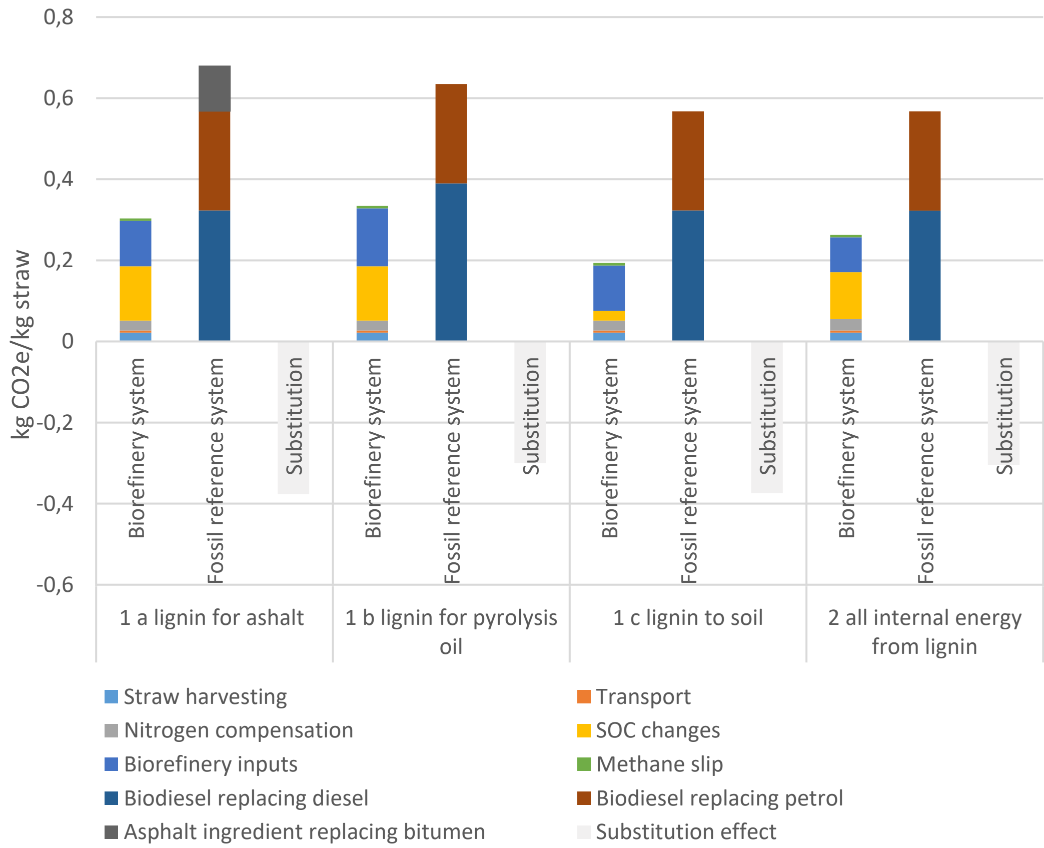

Figure 7. Climate impact (expressed in GWP100) for 1 kg DM straw processed in the biorefinery. The fossil reference system represents equivalent amount of products produced with fossil products. Substitution effects are calculated as climate impacts for the biorefinery system minus climate impact for the fossil reference system.

Substitution effects were highest for scenario 1a (lignin for asphalt) and scenario 1c (lignin to soil) (Figure 7), as also found using the time-dependent temperature response model (Figure 4).

4. Discussion

4.1. Biorefinery system considerations

4.1.1. The biorefinery process

Choice of yeast strain has importance for overall process performance of the biorefinery system. For example, the oleaginous yeast *R. toruloides* converts sugars to fat faster than the yeast strain assumed in the present study (*Lipomyces starkeyi*) (Brandenburg *et al.*, 2021). Further, *R. toruloides* can produce high-value chemicals (carotenoids) (Nagaraj *et al.*, 2022). Fermentation time can be very important to overall climate impact performance of the biorefinery (Karlsson *et al.*, 2017), because this step uses large amounts of electricity for agitation and aeration. Changing to a yeast strain that requires less time for the lipid accumulation step would lower the electricity use. In this study we assumed renewable electricity, which means that in a climate perspective the fermentation time will likely not be as important. However, it is important for the overall process energy demand and ultimately the cost of producing the yeast oil.In this study, glycerol generated in the transesterification step was assumed to be fed to the anaerobic biogas reactor, as done in Karlsson *et al.* (2016). Biogas production was thereby increased. It is worth noting that the glycerol could also have been used as a substrate for some other oleaginous yeasts (Chmielarz *et al.*, 2021), where it could have been converted to lipids and thereby boosted biodiesel and yeast biomass production.

4.1.2. Use of the biorefinery products

The lipids

There is currently a global deficit in dietary fats (Bajželj *et al.*, 2021). Apart from being used as biofuels, yeast could be a source of both protein and fat for humans (Jach *et al.*, 2022) or in animal feed (Blomqvist *et al.*, 2018). In a Swedish perspective, using oleaginous yeast grown on lignocellulosic materials could be an option for increasing vegetable fat production without relying too heavily on rapeseed oil production. Cultivation of rapeseed is constrained by climate (mainly grown in the south) and disease control considerations, *i.e*. rapeseed cannot occur too often in the crop rotation.

Lignin

There is currently strong interest in developing different applications for lignin (Wenger *et al.*, 2020). Lignin is a byproduct from many industrial systems processing lignocellulosic materials, but the characteristics of the byproduct will vary depending on the upstream processes used to isolate the lignin (Glasser, 2019). In this study, we examined the climate impact of alternative uses of the lignin byproduct from a lignocellulosic biorefinery using straw as feedstock and steam explosion as pretreatment. Lignin as a product from steam-exploded materials has been suggested for use in *e.g*. phenol resins (can be used to produce plastics), animal feed, aromatics (*e.g.* benzene) and bitumen (Moretti *et al.*, 2021). There are several other applications that could be of interest, however, and we are probably only seeing the beginning of development of lignin applications. In a climate impact perspective, it is of interest to store biogenic carbon in materials over long periods, with a potential climate mitigation effect.

4.1.3. Impact of geographical location

Straw harvesting for processing in a biorefinery is likely to occur relatively close to the biorefinery plant, as straw is a bulky material and long-distance transport is not economically feasible. A Swedish biorefinery using straw as feedstock would therefore likely be situated in southern Sweden, in an area with large amounts of cereal cropping. The area should also have low demand for straw for other uses, such as lower numbers of animals needing straw for bedding. In an assessment based on straw availability and possible offset for heat (district heating), Ekman *et al.* (2012) identified the counties of Skåne and Östergötland as promising regions for a straw-based ethanol plant.

Changes in SOC stocks proved to be important for the climate impact of the biorefinery system in all scenarios analysed in the present study except scenario 1c, where a large part of the lignin was returned to the soil. In the remainder of this section, we discuss the climate effects of SOC changes and factors that influence SOC stocks, while in Section 4.1.6 we discuss other environmental impacts from SOC changes.

Climate effects of SOC changes and factors influencing SOC stocks

Large amounts of carbon are stored as biogenic carbon in soils and in plant biomass, and soil carbon is the largest terrestrial carbon pool (Scharlemann *et al.*, 2014). This means that small changes in these pools can have relatively large effects on the CO_2 concentration in the atmosphere (Stockmann *et al.*, 2013). Harvesting straw means that less organic material is added to the soil, which in turn will affect the SOC stock in agricultural soil. The extent to which the stock is affected can vary depending on several factors, such as initial carbon concentration in the soil, soil type, climate and management practices (Bolinder *et al.*, 2020). Management practices that affects SOC include *e.g.* use of manure or cover crops or any practice that affects yield, since a higher yield level often involves higher inputs of carbon to the soil. In short, the actual effect on straw harvesting will depend not only on the fraction removed but also on other factors, including geographical location. In this study, we modelled SOC changes using the ICBM model, in which soil and climate conditions are considered (via the so-called r_e factor in the model). For the purposes of this study, we used soil and climate factors very close to the average soil and climate factors calculated for several of the most important agricultural production regions in Sweden (regions 1-5; Andrén *et al.* (2008)). When estimating SOC effects due to straw harvesting, consideration has to be taken of the local climate and soil factors, but also of management practices. Similarly to the effect on soil organic carbon losses, geographical location will also have an impact when assessing the SOC effects of lignin being returned to the soil.

Apart from the capacity of soil to sequester carbon from the atmosphere, increasing SOC content as a mitigation strategy has been discussed in relation to associated increased N_2O emissions. Guenet *et al.* (2021) concluded that the climate benefit of increased SOC stock is not likely to be fully offset by increased N_2O emissions, but that the climate benefit of carbon storage as SOC may be overestimated when this effect is not accounted for. Changes in N_2O emissions due to changes in SOC was not accounted for in the present study.

4.1.4. Implementation potential

Straw is a byproduct from production of cereal grains and other raw materials, and therefore its production does not compete directly with food production. In addition, its production will not cause major land use changes. There are many applications of straw, conventionally as animal feed and bedding, incineration for heat/electricity or as a substrate for edible mushrooms. Some straw is also inevitably left in the field, maintaining the soil carbon levels. The amount of straw produced is sufficient for these conventional applications and for biorefinery use, where after pretreatment it is a potential substrate for microbial fermentation to produce biofuels (ethanol and biodiesel), lipids for animal feed and biochemicals (Passoth & Sandgren, 2019).

There are several estimates of straw availability for energy purposes (Börjesson, 2016; Nilsson & Bernesson, 2009). The estimated potential depends on assumptions on future (cereal) production and constraints on the availability, such as ecological or economic constraints. In two previous straw availability studies (Börjesson, 2016; Börjesson *et al.*, 2013), straw availability in Sweden was estimated to be 2.5-25 TWh or around 0.5-5.0 million tonnes of straw yearly. Based on a simplified assumption that all of this straw is processed in the biorefinery concept described in this report and that the surplus lignin is used as asphalt amendment (scenario 1a), around 0.07-0.7 million tonnes of bitumen replacement product could be produced. Annual use of bitumen in Sweden is reported to be around 0.4 million tonnes (Aurell & Olsson, 2015).

4.1.5. Time perspective

Technology is available for most processing steps in the biorefinery concept assessed in the present study. The pretreatment steps (steam explosion and enzymatic hydrolysis) are similar to the corresponding steps in commercialised technology for ethanol production from lignocellulose biomass. The main challenge lies in extraction of lipids from the yeast biomass. Further, as already mentioned, different alternative uses for the lignin are currently being developed (Moretti *et al.*, 2021; Wenger *et al.*, 2020; Glasser, 2019). Some of these alternative uses are in the research stage and some are already being introduced on the market, *e.g*. bioplastics made from lignin (Lignin Industries AB, 2022) and concrete additives (Borregaard, 2022).

Building a biorefinery involves high capital investment and there is likely a need for long-term stability in government policy on renewable material and energy production to enable the required investment in the technology. Exploring alternative uses of byproducts, such as the lignin-rich byproduct, could be beneficial for the overall economics of the system and thereby attract investment. These aspects are further discussed below.

4.1.6. Sustainability aspects

Environmental aspects

This study assessed the climate impact of different applications of lignin from a biochemical biorefinery converting straw to energy, primarily energy carriers. We compared the biorefinery system to a fossil system with equivalent amounts of fossil fuels or, in the case of scenario 1a (lignin for asphalt) with fossil bitumen. These fossil products are currently the most common on their respective market. However, in the time period considered in the present study (100 years), this will likely change to more renewable products and fuels. Differences between the reference system and the biorefinery system will therefore change over time.

Impacts on climate change from SOC changes are discussed in section 4.1.3. However, the amount of carbon in the soil is also important in other regards. Soil organic carbon quantity and quality is important for soil health and for many functions of the soil (Lal, 2014). Further, elevated SOC content can increase the productivity of agricultural land (*i.e.* crop yields) (Lal, 2004).

In a sustainability perspective, the main reason for using straw as biorefinery feedstock is that straw can be regarded as a byproduct from cereal cropping, meaning that no additional land is needed to produce the feedstock. However, if straw is harvested unsustainably so that SOC is depleted, there is a risk of long-term negative effects on crop yields, and this could indirectly increase the demand for land for agricultural production.

Social aspects

In contrast to technical and environmental aspects of lignin utilisation, the social aspects have gained little attention in previous studies. A review by Wenger *et al.* (2020) identified several important social-economic factors affecting the potential for lignin-based products to enter the market. One such factor is policy-related issues, including promotion of technological innovations, promotion of cross-sectoral networks, development of labelling, compliance with regulation, regulatory approval and permits for facility changes. In addition, Wenger *et al.* (2020) identified cultural issues such as communication /cooperation between stakeholders, collaborations between sectors along the new value chain and reduction of information asymmetries.

On a larger scale, introduction in Sweden of a straw-based biorefinery that could produce biodiesel and biogas, combined with lignin-rich byproducts, would enable higher production of domestic energy and thereby potentially increase energy security. The Swedish market for liquid biofuels is heavily dependent on imports (Energimyndigheten, 2020), and the sector is therefore reliant on other regions of the world to deliver vegetable and animal oils (in the case of biodiesel production).

Economic aspects

In their recent review, Wenger *et al.* (2020) concluded that finding alternative uses (compared with combustion for energy) for the lignin-rich byproducts from a straw-based biorefinery is important for overall biorefinery economics. However, although some lignin-based products have entered the market, large-scale commercialisation of lignin has not yet occurred (Wenger *et al.*, 2020). Much research to date has focused on lignin from the pulp and paper industry, *i.e.* from forest-based biorefineries, with less attention to lignin from other sources, such as straw.

In terms of the economics of cereal farming, a biorefinery processing straw would create a market for straw, which would increase revenue for cereal farmers. This effect would likely be local, in the area close to the biorefinery.

5. Conclusions

Harvesting straw for use in a biorefinery for production of biofuels and other applied products was found to be more beneficial in terms of overall climate than a fossil reference system. This was true even when soil organic carbon losses due to straw harvesting were included.

Three different applications for the lignin-rich byproduct from the biorefinery were assessed (asphalt amendment, pyrolysis oil, soil amendment). In a climate impact perspective, the most beneficial application for the lignin byproduct was as asphalt amendment or soil amendment. The asphalt alternative appeared even more promising when the effect of carbon storage in the asphalt was considered. However, this effect depends on road lifetime (a few decades) and there are uncertainties related to the fate of the biogenic carbon in the asphalt through its lifetime. Use of lignin as pyrolysis oil had a similar climate impact as a scenario in which the lignin was used to meet all internal energy demand in the biorefinery.

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