A comparative life cycle assessment and toxicity evaluation of impregnated railway sleepers

Creosote and linseed oil

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In cooperation with RISE AB and Linjonwood AB.
Summary

A comparative life cycle assessment (LCA) of impregnated wooden sleepers is presented in this report. The included impregnation oils are linseed oil and creosote, and the environmental aspects considered here are climate change, ecotoxicity, human toxicity and the use of fossil resources.

The results of the LCA indicate that the carbon footprint of the linseed oil sleeper is equal to or higher than the carbon footprint of creosote. The main contributors to the linseed oil’s carbon footprint are emissions of nitrous oxide and carbon dioxide from the use of fertilizers on the farmland and carbon dioxide emissions from fossil fuels used in tractors, lorries and for the production of steam and electricity used in the production process.

Considering the ecotoxicity and human toxicity, the results indicate that the creosote sleeper performs worse than the linseed oil sleeper, which might be expected. However, depending on how the environmental burdens of linseed oil, linseed cake and straw are allocated between them (mass or economical allocation) the results for the linseed oil sleeper vary to a large extent.

The results are associated with some uncertainties: for example, no full-scale production plant for linseed oil sleepers exist today meaning that the input data to some extents are based on estimations.

To reduce the carbon footprint of sleepers impregnated with linseed oil, a few measures were identified. For example, by changing from diesel in tractors and trucks in the agriculture of linseed, as well as natural gas in the production process to renewable fuels. The carbon footprint can also be decreased by reusing the sleepers after their use phase.
1 Introduction

As a part of the VINNOVA funded project MiBO (Non-toxic and Sustainable impregnation of wood with bio-based oil), an environmental evaluation in a life cycle perspective of wood impregnated with linseed oil was performed. In this report, the results of the life cycle assessment are presented.

The LCA was performed on a case of impregnated wooden sleepers, or railway ties, where the environmental impacts of a sleeper impregnated with linseed oil was compared to those of a sleeper impregnated with creosote.

Creosote is today used to a large extent as a wood preservative for both sleepers and utility poles. The continued use of the wood preservative is debated due to it being carcinogenic and its content of toxic substances, which is why the use of creosote is strictly limited (Kemikalieinspektionen, 2023). The need for a sustainable and non-toxic wood impregnation is therefore of high importance. To assess the environmental sustainability of both linseed oil and creosote, an LCA was performed within the MiBO project.

1.1 What is LCA?

Life cycle assessment (LCA) investigates the environmental impacts related to a product or a system during its whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including material production, manufacturing, use and maintenance, and end-of-life (see figure below).

LCA is a widely used and accepted method for studies of environmental performance of various products and systems. The LCA in this report is to a large extent performed in accordance with ISO 14040:2006 and ISO 14044:2006 standards.

Figure 1. Illustration of an LCA system.
1.2 Disclaimer

The results of this study have not been subject to a third-party review, as recommended by ISO 14040:2006 and 14044:2006. The results have been internally reviewed in accordance with IVL’s reporting policy.
2  Goal and scope

The **goal** of this study is to make a comparative LCA of two variants of railway sleepers: sleepers impregnated with creosote and with linseed oil. The aim is also to analyse hot spots within the life cycle of the railway sleepers.

In a comparative LCA, the aim is to compare the differences between the alternatives which means that some parts and life cycle stages may be excluded due to similarities. The aim is not to make a complete LCA of a railway sleeper.

The **functional unit**, or reference unit, in this study is one railway sleeper. The weight of one sleeper excluding impregnation is 60 kg.

This study is a **cradle-to-grave** LCA which implies that the environmental impact from raw material production, to manufacturing, to use of the product and finally to the waste treatment is included in the system boundaries. Some life cycle phases have been excluded in line with the study’s goal, see the section below for more information.

2.1  Limitations and important assumptions

In the list below, relevant limitations and important assumptions are presented which may affect the results to some extent. Limitations may, for instance, be caused by lack of data or a specific goal and scope which limits the study’s use in other applications.

- The life span is set to be the same for both creosote and linseed oil sleepers. No specific life span measured in years is set since the aim of the study is to make a comparison between the two options. Only relative changes are of interest. This assumption is tested in a sensitivity analysis where the life span of linseed oil sleepers is increased.
- The consumption of wood impregnation oil is 4 kg for the creosote sleeper and 10 kg for the linseed oil sleeper.
- Installation and deconstruction are excluded in this study since they are equal for both sleeper types.
- Decontamination of the site after the creosote sleeper has been deconstructed is not included here due to lack of data.
- It is assumed that 70% of the creosote leaks to the environment during the use phase. The corresponding number for linseed oil sleepers is 28%. It is however not established whether it leaks out to the environment or whether it is polymerized and thus not detectable as linseed oil in the lab analysis. A conservative assumption was made here, and it is assumed that 28% of linseed oil is leaked out.
- It is assumed that the carbon in the creosote oil which is leaked out during the use phase will oxidize and emit as carbon dioxide to air. This is related to some uncertainties since it is unclear how much of the oil will be oxidized. It is therefore marked as a lined bar in the results.
- No toxicity data for the wooden sleeper production was available. However, this is deemed to have an insignificant impact on the results.
2.2 Environmental impact categories

Four environmental impact categories and one inventory indicator are included in this study, and they are:

- Global warming potential (fossil), kg CO₂ eq., IPCC 2013.
- Ecotoxicity potential, CTUₑ, Usetox 2.12.
- Human toxicity potential (carcinogenic), CTUₕ, Usetox 2.12.
- Human toxicity potential (non-carcinogenic), CTUₕ, Usetox 2.12.
- Use of non-renewable primary energy, MJ.

No biogenic carbon uptake nor emissions have been included. This is because the expected life span of the products in this study is shorter than 100 years thus no carbon storage occurs.

Further on in this report, the expression carbon footprint entails the products’ global warming potential while the term environmental footprint considers all included environmental categories in this study.
3 Inventory analysis

In this chapter, the inventory analysis is presented. This chapter contains a detailed description of the data used in the study.

For both sleeper types, the same data for wooden sleeper production have been included (i.e., a sleeper without impregnation). The sleeper weighs 60 kg for both cases and data for sleeper production have been taken from an EPD (Bitterna Såg & Trävaru AB, 2023). The data is valid for production in Sweden and the sleepers meet the standard according to the Swedish Transport Administration.

3.1 Creosote sleeper

Creosote oil is assumed to be produced in Europe and imported to Sweden for impregnation of sleepers. 4 kg of creosote is assumed to be used for impregnating one wooden sleeper (Crona & Bydén, 2012).

The life span of the creosote sleeper is not specified here since the aim of the study is to compare the two types of sleepers, and it is therefore assumed that the life span of the linseed oil sleeper is the same as for the creosote sleeper. The technical life span of a wooden sleeper varies, for example, depending on the mechanical strain and the surrounding environment, and a fully functioning wooden sleeper might be changed before it reaches its technical life span if other sleepers on the same track is exchanged due to mechanical strains.

In the table below, information on which data sources have been used in different life cycle stages is presented.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Amount</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wooden sleeper</td>
<td>60 kg</td>
<td>Bitterna EPD</td>
</tr>
<tr>
<td>Creosote oil</td>
<td>4 kg</td>
<td>Ecoinvent version 3.8</td>
</tr>
<tr>
<td>Impregnation, electricity</td>
<td>0.15 kWh</td>
<td>El Harthy, 2017</td>
</tr>
<tr>
<td>Impregnation, emissions</td>
<td>5% of creosote oil emitted to air and freshwater</td>
<td>Ecoinvent version 3.8</td>
</tr>
<tr>
<td>Use phase, emissions</td>
<td>70% of creosote oil emitted to air and industrial soil</td>
<td>Ecoinvent version 3.8</td>
</tr>
<tr>
<td>Waste treatment (incineration)</td>
<td>60 kg wood + 1.2 kg creosote (approx. as hard coal). Energy credits 82 MJ electricity and 802 MJ heat.</td>
<td>Sphera managed LCA content, database version 2022.2.</td>
</tr>
</tbody>
</table>

In the figure below, the flow scheme of the most important mass flows is presented for the creosote sleeper. The figure only includes upstream flows, and they are not allocated. In the case of coking, an energy-based allocation procedure has been applied in the LCA model in accordance with the chosen Ecoinvent methodology. Coke and coal gas have energy contents of 28 and 35 MJ/kg.
respectively. The environmental burdens associated with coking is distributed between production of coke, coal tar, benzene, and coal gas.

![Flow scheme to produce a creosote impregnated sleeper. The flows are not allocated in this figure.](image)

### 3.2 Linseed oil sleeper

Two scenarios for linseed oil impregnated sleepers have been included in the results of this study.

**Alternative 1:** Economically allocated linseed oil, cobalt siccative, and incineration with energy recovery as waste treatment option.

**Alternative 2:** Mass-based allocated linseed oil, manganese siccative, and reuse as end-of-life option.

The linseed oil is assumed to be produced in Europe and imported to Sweden for impregnation of sleepers. Unlike the creosote option, this sleeper option is not on the market in Sweden today which means that some assumptions have been made to construct a relevant scenario. 10 kg of linseed oil is needed to impregnate one wooden sleeper.
The life span of the linseed oil sleeper is assumed to be the same as for the creosote sleeper. Different options are tested in a sensitivity analysis.

In the table below, information on which data sources have been used in different life cycle stages is presented.

Table 2. Inventory analysis and data sources used for the models of the linseed oil sleepers.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount</td>
<td>Reference</td>
</tr>
<tr>
<td>Wooden sleeper</td>
<td>60 kg</td>
<td>Bitterna EPD</td>
</tr>
<tr>
<td>Linseed oil</td>
<td>10 kg</td>
<td>Agri-footprint, Crude linseed oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(economic allocation)</td>
</tr>
<tr>
<td>Siccative (cobalt or manganese)</td>
<td>0.01 kg</td>
<td>Sphera managed LCA content, database version 2022.2.</td>
</tr>
<tr>
<td>Impregnation, electricity</td>
<td>0.15 kWh</td>
<td>El Harthy, 2017</td>
</tr>
<tr>
<td>Use phase, emissions</td>
<td>28% of linseed oil emits to industrial soil</td>
<td>28% of linseed oil emits to industrial soil</td>
</tr>
<tr>
<td>Waste treatment (incineration or</td>
<td>60 kg wood + 7.2 kg linseed oil. Energy credits 99 MJ</td>
<td>Sphera managed LCA content, database version 2022.2.</td>
</tr>
<tr>
<td>reuse)</td>
<td></td>
<td>Electricity and 970 MJ heat.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>kg linseed oil. Material credits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67.2 kg construction timber.</td>
</tr>
</tbody>
</table>

In the figure below, the flow scheme of the most important mass flows is presented for the linseed oil sleeper. The figure only includes upstream flows, and they are not allocated. In the case of linseed cultivation and linseed oil production, two allocation procedures (mass- and economic) have been applied in the LCA model in accordance with the chosen Agri-footprint methodology.

The linseed used as input is modelled as a market mix, and the two main linseed producers are Russia (57%) and Canada (31%). The rest is produced in Germany, Great Britain, France, Belgium, US, Latvia, and Ukraine according to the data applied in this study.

The data for linseed oil production is based on a cold pressed linseed oil. This implies that for one tonne of linseed going into the process, 350 kg oil and 640 kg linseed meal, or linseed cake, is produced. The oil yield would be higher for a warm pressed linseed oil; however, the quality of the oil would be lower since more impurities would be extracted from the linseed.
Figure 3. Flow scheme to produce a linseed oil impregnated sleeper. The flows are not allocated in this figure.

In the scenario where the linseed and linseed oil are economically allocated, the following prices have been adopted in the calculations according to the LCA database Agri-footprint:

Table 3. Prices used for economic allocation for linseed and linseed oil.

<table>
<thead>
<tr>
<th>Linseed cultivation</th>
<th>Linseed oil production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linseed</td>
<td>Linseed oil</td>
</tr>
<tr>
<td>0.3 £/kg</td>
<td>1019 $/ton</td>
</tr>
<tr>
<td>Straw</td>
<td>Linseed cake</td>
</tr>
<tr>
<td>0.05 £/kg</td>
<td>279 $/ton</td>
</tr>
</tbody>
</table>

In this study, it is assumed that a siccative is added to the linseed oil to decrease the drying time. Two common siccatives used are cobalt and manganese. According to the product sheets of two suppliers, the maximum addition of siccative is 0.01% in relation to the metal content. The amount of manganese siccative added is twice the amount as cobalt.
Unlike the creosote sleeper, the linseed oil sleeper can be reused at the end-of-life stage since no toxic impregnation substance is used. Depending on the quality of the sleeper, the sleeper can either be reused in outdoor applications or incinerated if mechanical strains occur.
4  LCA results

In this chapter, the LCA results are presented. The results are divided into different environmental categories.

4.1  Global warming potential

In the figure below, the results for the global warming potential are presented. Two alternatives for linseed oil sleepers are presented (see chapter 3 above) and compared to one scenario for a creosote sleeper. The impact is divided into different life cycle stages and the bars on top display the total result: all life cycle stages added together.

![Global warming potential](image)

Figure 4. Global warming potential for a creosote sleeper and two scenarios for linseed oil sleepers. The result is expressed in kg carbon dioxide equivalents per sleeper.

According to the graph above, the results indicate that for the linseed oil sleepers it is the production of 10 kg linseed oil which contributes most to the total carbon footprint. It is also clear to see that the results can vary a lot depending on which allocation procedure is chosen. The results can vary with 100% depending on if the co-products are allocated based on mass or on economical figures. This results in large uncertainties related to the LCA results.
For creosote, it is the use phase which potentially has the largest impact during its life cycle. As mentioned above, this is also related to some uncertainties since it is not certain that 100% of the carbon in the creosote oil will oxidise and be emitted as carbon dioxide. The emissions during the use phase are included in the total results. The remaining creosote in the sleeper after the use phase contributes with carbon dioxide emissions during the incineration. No carbon dioxide of fossil origin will be emitted during the incineration of the linseed oil sleeper (alternative 1).

4.2 Use of non-renewable primary energy

In the figure below, the results for the primary energy use are presented. Two alternatives for linseed oil sleepers are presented (see chapter 3 above) and compared to one scenario for a creosote sleeper. The impact is divided into different life cycle stages and the bars on top display the total result: all life cycle stages added together.

Figure 5. Non-renewable energy use for a creosote sleeper and two scenarios for linseed oil sleepers. The result is expressed in MJ per sleeper.

As the results above indicate, linseed oil sleepers have an equal or lower use of non-renewable energy during its life cycle as the creosote sleeper, which might seem surprising considering that linseed oil is a renewable material unlike creosote. However, the results are highly dependent on if the linseed oil is allocated based on economic figures or based on mass. Modern agricultural systems are dependent on fossil fuels, partly for diesel used in machinery and partly for fertilizers. The production of linseed oil also demands electricity and heat, which are in part fossil based.
Creosote is entirely comprised of fossil resources (coal) which explains the high footprint of non-renewable energy.

4.3 Ecotoxicity potential

In the figure below, the results for the ecotoxicity potential are presented. Two alternatives for linseed oil sleepers are presented (see chapter 3 above) and compared to one scenario for a creosote sleeper. The impact is divided into different life cycle stages and the bars on top display the total result: all life cycle stages added together.

Figure 6. Ecotoxicity potential for a creosote sleeper and two scenarios for linseed oil sleepers. The result is expressed in CTUe (Comparative Toxic Unit ecotoxicity) per sleeper.

According to the results above, it is indicated that it is the creosote sleeper which has a relatively high ecotoxicity potential in comparison to the linseed oil sleepers. The main impact comes from the production of creosote, but the impregnation process as well as the emissions during use phase contributes to the overall results. During the production of creosote, it is emissions of aluminium and iron to freshwater which contributes to the results but during the impregnation and use phase it is emissions of pyrene to freshwater which has the highest ecotoxicity potential.

For the linseed oil sleeper, it is the insecticides, herbicides and fungicides which are used during linseed cultivation which contributes to the ecotoxicity potential. In comparison to the creosote sleeper the potential is low, even though a metal-based siccative is used for the linseed oil.
4.4 Human toxicity potential (carcinogenic)

In the figure below, the results for the human toxicity potential (carcinogenic) are presented. Two alternatives for linseed oil sleepers are presented (see chapter 3 above) and compared to one scenario for a creosote sleeper. The impact is divided into different life cycle stages and the bars on top display the total result: all life cycle stages added together.

![Diagram of human toxicity potential (carcinogenic)](image)

**Figure 7.** Human toxicity potential (carcinogenic) for a creosote sleeper and two scenarios for linseed oil sleepers. The result is expressed in CTUₜₕ (Comparative Toxic Unit human toxicity) per sleeper.

In the results above, it is indicated that the creosote sleeper has the highest human toxicity potential in comparison to the linseed oil sleepers, with regards to substances and exposure paths which can cause cancer among humans. During the impregnation step of the creosote sleeper, emissions of fluoranthene, pyrene and phenanthrene causes the highest human toxicity potential. The reason why the use phase has a much lower potential than the impregnation step is likely due to that emissions which occur during the use phase are emitted to industrial soil rather than freshwater. In comparison to the creosote sleeper, the human toxicity potential for the linseed oil sleepers is very low, independent of the choice of allocation procedure.
4.5 Human toxicity potential (non-carcinogenic)

In the figure below, the results for the human toxicity potential (non-carcinogenic) are presented. Two alternatives for linseed oil sleepers are presented (see chapter 3 above) and compared to one scenario for a creosote sleeper. The impact is divided into different life cycle stages and the bars on top display the total result: all life cycle stages added together.

![Human toxicity potential (non-carcinogenic) graph]

Figure 8. Human toxicity potential (non-carcinogenic) for a creosote sleeper and two scenarios for linseed oil sleepers. The result is expressed in CTUh (Comparative Toxic Unit human toxicity) per sleeper.

The results above indicate that it is the production of creosote and linseed oil which has the largest toxicity potential out of all life cycle stages. For the creosote it is mainly emissions of arsenic and zinc to freshwater during production which contributes to the toxicity potential, while for the linseed oil it is emissions of heavy metals to agricultural soil during linseed cultivation which has an impact. The choice of allocation method for the linseed oil has a major influence on the results in this analysis.
5 Additional toxicity considerations

In this chapter the result from an exploratory sub-study where chemical health risks to humans are highlighted is presented. Since the study does not follow the system boundaries of LCA the study and its results are presented as a separate chapter. Comparison of the creosote and linseed oil impregnated sleepers was performed with the ProScale method that covers toxicity potential due to direct exposure of humans in the working environment.

5.1 What is ProScale?

ProScale is a method for a scoring system based on both hazard and exposure for comparing direct chemical risks to workers, professionals and consumers associated with products in a life cycle perspective. By using the ProScale method an additional perspective of toxicological impact of direct exposure on humans during the production phase of the products are added.

The ProScale™ method has been developed during 2016-17 in an industry consortium with expertise both from the Life cycle assessment and Risk assessment areas (Rydberg et al, 2017; ProScale, 2017). The founding members being BASF, Covestro, Deutsche Bauchemie, DSM, IVL, Kingspan and Solvay. The purpose of the development was to achieve an easy-to-use method for assessing direct-exposure related Human Toxicity Potentials for product systems (LCA perspective), ideally compatible with Product Environmental Footprint (PEF).

The ProScale methodology can in a simplified way be described using Equation 1, where: PSS denotes the ProScale Score; HF is the Hazard Factor for a substance, derived based on substances classification in the GHS/CLP classification system, reflecting health effect severity and potency based on Hphrase and OEL or DNEL; ECF is the Exposure Concentration Factor, and describes the exposure of a substance based on exposure modelling using a tier 1 exposure model (Based on ECETOC TRA, v3); PHF is a Person-Hour Factor describing the person-hours of work needed per unit output or input of a process (product or service); and MF is the Mass Flow, describing the amount of a substance needed to produce a product (kg per functional unit). ProScale scores are derived separately for inhalative, oral and dermal exposure routes. More information about the ProScale method is found in the guiding document, A life cycle-oriented method to assess toxicological potentials of product systems (ProScale, 2017).

Equation 1: \[ PSS = HF \times ECF \times PHF \times MF \]

5.2 Goal and Scope for sub-study

In this section, the goal and scope of the additional toxicity study using the Proscale methodology is defined and explained. This sub-study is separated from the rest of the LCA study since the Proscale methodology is used for assessing direct human toxicity impact potential. The values of human toxicity potential presented in chapters 4.3 and 4.4 are delimited to indirect exposure routes that could lead to cancer and non-carcinogenic toxicity potentials. With the Proscale methodology direct exposure routes are taken into consideration. The results will give information on how extensive the chemical risk is for workers, professionals and consumers associated with the
production of creosote impregnated and linseed oil impregnated sleepers in a life cycle perspective.

5.2.1 Goal

The goal of this study is to assess the direct human toxicity potential resulting from the production of creosote impregnated and linseed oil impregnated sleepers by using the ProScale method and identify which processes in the life cycle of the two different sleepers that have the largest contribution to inhalation and dermal direct human toxicity potential (contribution analysis).

5.2.2 Scope

The study aims at investigating the direct human toxicity potential, for both inhalation and dermal, using ProScale, to produce sleepers impregnated with creosote and linseed oil.

The assessment is focusing on the production and the upstream processes for producing the raw materials in the impregnated sleepers. The usage of two different desiccants, cobalt based and mangan based desiccant have also been evaluated.

5.2.2.1 Type of LCA

The study is an attributional LCA, where the direct human toxicity potential is assessed for the railway sleepers.

5.2.2.2 Functional unit

The functional unit, or reference unit, in this study is one impregnated railway sleeper. The lifetime of the railway sleeper is not considered as a parameter since the use phase is not included in the study.

5.2.2.3 Studied product systems

The studied products systems are described in detail below. The flowcharts describe which processes that have been included in the assessment.

Data describing the production of wood sleeper, have been used for both systems, impregnation with creosote and impregnation with linseed oil. Since the focus is on the impregnation substance the process steps planting, harvesting, drying and debarking, and turning have not been included in the study.

The impregnation of the sleeper is assumed to take place at the manufacturing site. Estimated data was used for the impregnation process.

The drying of impregnated sleepers, installation of sleepers, use phase, deconstruction and waste management are not included in this assessment since the scope based on resources available was defined as cradle to gate until and including production of the sleeper.

Wood sleeper impregnated with creosote

The considered life cycle stages, from a cradle to grave perspective, for the impregnated sleeper, are shown in Figure 9. The creosote is produced from coal via the production of coal tar.
During the use phase, the creosote impregnation on the sleeper leaches and thus could affect humans in the surrounding area. However, this process is not included in the study.

**Figure 9 Overview of the life cycle of the sleeper impregnated with creosote.** The green boxes are the processes included in the assessment and the grey boxes are the processes not included.

**Wood sleeper impregnated with linseed oil with desiccant**

The considered life cycle stages, from a cradle to grave perspective, for the railway sleeper, are shown in Figure 10. The linseed oil is produced from cultivation of linseed.

Cultivation of linseed and production of linseed oil was included in the product system as well as the production of the desiccant. The production of desiccant has not been included in the system as its contribution to the result can be assumed to be negligible.
Figure 10 Overview of the life cycle of the sleeper impregnated with linseed oil. The green boxes are the processes included in the assessment and the grey boxes are the processes not included.

5.2.2.4 System boundaries-
This study has the scope of cradle-to-gate LCA which implies that the direct human toxicity impact from raw material production to manufacturing is included in the system boundaries. The production of most of the raw materials are included. The production of the sleepers is not included since focus lies on the impregnation substance. The production of fuel and generation of electricity is not included because of time constraints. For the same reason, the transportation of the raw material and products are not included.

5.2.2.4.1 Allocations
ProScale of Unit process (PSU) describes the toxicological potential of all substances involved in one unit process. A unit process could for example be the distillation process of coal tar, where a separate PSU score is calculated for each exposure route (inhalation or dermal). One unit process can have multiple outputs such as e.g., the distillation process of coal tar generating creosote and coal tar pitch. For such unit processes allocation of the ProScale score of the unit process (PSU) is needed. Conventional options are allocation based on mass, economy, or energy. In this study, the ProScale score for the unit process (PSU) is divided by the total mass of all outputs, meaning that the distillation process contribution to the product score for all different products from (in this case) the distillation will be the same for each kg of output.

5.2.2.5 Limitations and assumption
The following limitations and assumptions have been made:

- Material and product flows are considered but not elementary flows such as emissions from the processes into the environment.
- The assessment is in the system boundary cradle to gate.
- The generation of electricity is not included.
- Extraction and processing of fuel used in the processes are not included.
- The transportation of material and fuel are not included.
Report C 776 – A comparative life cycle assessment and toxicity evaluation of impregnated railway sleepers – Creosote and linseed oil

- Intermediate storage after impregnation is not included.
- When calculating the impact of railway sleepers, data for the production of utility poles has been used instead of specific data for railway sleepers. The same process, "Production of wood utility poles" has been used in the calculations for both creosote and linseed oil impregnated railway sleepers.

5.3 Life cycle inventory analysis

This section gives an overview of the data collection process and the information collected and used in the analysis. The collected data are inputs and outputs of material, chemicals, products, and energy (fuel and electricity), which is complemented with ProScale specific data.

Generic data for upstream processes were collected from Ecoinvent version 3.8, Agri-footprint, and literature. The mass- and energy flows are together with ProScale specific data documented in a data collection template specifically developed for ProScale assessments. Thereafter, all the data is inserted to a webtool used for making ProScale assessments.

Data for production of utility poles have been used when calculating the exposure from the production of sleeper and data for utility pole production originates from site specific data from the producer Rundvirke (Gunnarsson et al, 2020).

ProScale specific data are needed to determine the Hazard Factor (HF), the Exposure Concentration Factor (ECF) and Person-Hours Factor (PF). Data collected to determine the HF are hazard classifications (H-phrases) of substances and materials and occupational exposure limits (EOLs). Hazard classifications and OELs are usually found at the European Chemicals Agency (ECHA). The data and information needed to determine the ECF are technical descriptions of the processes studied and a substance or material’s fugacity (likelihood of becoming airborne). The technical description is needed to translate the studied process into a generic process category (PROC). The fugacity for a liquid is determined by its vapour pressure, while the fugacity for a solid is determined by its dustiness. The PF is the number of person-hours worked per amount of production.

5.4 Results and discussion

In this section, the result of the study is presented. The values showed in the following section should be read with caution, being preliminary and not independently reviewed yet.

5.4.1 Contribution from different processes (contribution analysis)

The result from the contribution analysis for creosote impregnated sleeper and linseed impregnated sleeper are presented below. Presented results represents the ProScale scores of unit processes (PSUs).
5.4.1.1 Creosote impregnated sleeper

The toxicity potential from direct exposure to humans in three unit processes involved in the production of one creosote impregnated sleeper has been calculated. A unit process is the smallest element considered in the life cycle inventory analysis for which input, and output data are quantified. The three unit processes involved are production of coal tar, production of creosote and the impregnation process. For each process, calculations were performed for both inhalation and dermal exposure, see Figure 11-12. There is a noticeable difference in the ProScale scores of the unit processes (PSU score) for inhalation exposure compared to dermal exposure across all processes. The highest score for inhalation and dermal exposure was generated from the impregnation process which indicates the highest potential for toxicity exposure within this process compared to the other two processes. One reason for the lower scores is that these processes generated several products (outflows) to which the PSU score is allocated, which means that there are other products produced within these processes that share the generated toxicity potential. The allocation step is not included in the impregnation process since the only outflow is the creosote impregnated sleeper, consequently, it is the inherent toxicity within creosote that contributes to the final scores. The risk for exposure will also be affected by how the process is conducted. Pyrolysis is the process performed in the unit process 1 (production of coal tar) and 2 (production of creosote). Since the processes are performed in a closed container, the risk of getting exposed is lower compared to the impregnation process where there is a higher risk of exposure when the wood is transferred from the vacuum container.

![Figure 11 ProScale scores of the unit processes (PSU score) for inhalation exposure for the different process steps of creosote impregnated sleeper.](image-url)
Figure 12 PSU scores for dermal exposure for the different process steps of creosote impregnated sleeper.
5.4.1.2 Linseed oil impregnated sleeper

To speed up the drying process of linseed oil a desiccant is added to the oil. There are several desiccants on the market but the most used are cobalt-based and manganese-based desiccants. In Figure 13-14 below, results for linseed oil impregnated sleeper with cobalt-based desiccant is presented. The production process of cobalt desiccant and the impregnation process will generate a higher PSU score indicating a higher toxicity exposure compared to when manganese desiccant is used, Figure 15-16. The higher PSU score is due to a higher inherent toxicity of cobalt and that the double amount of cobalt-based desiccant is used in the process compared to the manganese-based desiccant.

The usage of manganese-based desiccant result in a lower toxicity exposure, however the greatest toxicity impact comes from the process of linseed cultivation. Looking closer at the cultivation process of linseed in Figure 17-18, the usage of diesel gives the greatest contribution to the total PSU score of the process.

To improve the working environment and reduce the risk of toxic exposure, it is important to find a good alternative fuel that is better than diesel in terms of toxicity.

Figure 13 PSU scores for inhalation exposure for the different process steps of linseed oil impregnated sleeper, cobalt based desiccant.
Figure 14 PSU scores for dermal exposure for the different process steps of linseed oil impregnated sleeper, cobalt based desiccant.

Figure 15 PSU scores for inhalation exposure for the different process steps of linseed oil impregnated sleeper, manganese-based desiccant.
Figure 16 PSU scores for dermal exposure for the different process steps of linseed oil impregnated sleeper, manganese-based desiccant.

Figure 17 PSU scores for inhalation exposure for the different flows in the process of linseed cultivation.
5.4.1.3 Comparison between creosote and linseed oil impregnated sleepers

The results show that there is a significant difference between the values when using a creosote impregnation compared to linseed oil. The total score for inhalation exposure from all processes involved to get one impregnated sleeper is around two orders of magnitudes higher when using creosote as impregnation compared to linseed oil (regardless of the desiccant used). This indicates that the toxicity and potential of getting exposed is much higher when creosote is used compared to linseed oil. The total score for dermal exposure is slightly lower for both creosote and linseed oil compared to inhalation exposure which means that the risk of coming into contact with the impregnation agent is much lower compared to the risk of an airborne inhalative exposure. However, the risk of dermal exposure is still much higher when using a creosote impregnation.
6 Interpretation

In this chapter, the results interpretation is presented. To test a few of the assumptions made in the study two sensitivity analyses are performed and a contribution analysis to analyse the linseed oil’s environmental impact.

The environmental impacts have not been normalised nor weighted to be able to compare them to each other. In general, this adds uncertainties to the results and has thus not been performed within the scope of this study.

6.1 Contribution analysis: linseed oil

To get a better understanding of which activities contributes the most to the linseed oil’s carbon footprint, the most important activities are displayed in the pie charts below. The chart only considers the carbon footprint related to the production of linseed oil and no downstream activities. No comparison to creosote is made here. In the figure below, the relative contribution to global warming potential is presented.

![Pie chart showing contributions to global warming potential for linseed oil](image)

As indicated in the results above, the most important activity which influences the carbon footprint of linseed oil is the linseed cultivation, which represents 41% of the linseed oil’s footprint. During the cultivation, emissions of carbon dioxide from lime and urea, as well as emissions of nitrous oxide, occurs as a result of fertilizing the soil. Both direct and indirect emissions of nitrous oxide...
are considered here. These emissions might be difficult to change or improve, but other activities in the production chain may be easier to affect, such as the use of fossil fuels for production of steam, electricity, and diesel.

6.2 Sensitivity analysis: including credits beyond the life cycle

The first sensitivity analysis tests how the results differ if we also include the benefits outside of the system boundaries, i.e., energy recovery from incineration and material recovery from reuse. In this sensitivity analysis only global warming potential is considered.

In the figure below, the results are presented. The dashed columns represent a potential climate benefit through system expansion where the produced energy replaces other energy sources in a district heating grid and the recycled material replaces a primary construction timber. In this analysis, the heat and electricity are assumed to replace heat from biofuels and an average Swedish electricity grid mix since the waste treatment is in Sweden rather than in Europe. If these assumptions were to be changed, the results would also change.

![Graph showing global warming potential (fossil) for different sleepers.](image)

**Figure 20.** The results of global warming potential considering potential climate benefits outside of the system boundaries. The net impact displays the credits added to the total impact.

The results indicate that the net benefit of reusing the linseed oil sleeper after its use (alternative 2) is bigger than the potential emissions of greenhouse gases occurring during the production, use and waste treatment. The differences of climate benefits from energy recovery between the creosote sleeper and the linseed oil sleeper (alternative 1) are small, however, the linseed oil sleeper has a higher energy content due to the higher use of oil and lower leakage during the use phase.
6.3 Sensitivity analysis: changing the expected life span of sleepers

The second sensitivity analysis tests how the results may change if the linseed oil sleeper in fact has a longer expected life span than the creosote sleeper, which have been implied through field tests (according to findings in WP2) and which shows the rot resistance of impregnated wood. The analysis only considers global warming potential, and credits beyond the life cycle are not included. The results are presented in the table below.

By keeping the life span of the creosote sleeper constant and increasing the life span of the linseed oil sleepers it is possible to see that both linseed oil sleeper alternatives may have an equal or lower carbon footprint than the creosote sleeper if the life span increases with 50% in comparison to the creosote sleeper. At this alternative, both sleepers potentially have a lower, or slightly lower, carbon footprint than the creosote sleeper (the results are less than 100%).

Table 4. The results of global warming potential considering a longer life span for the linseed oil sleepers (+25% and +50% in life span).

<table>
<thead>
<tr>
<th>Expected life span:</th>
<th>Same for all alternatives</th>
<th>+ 25% increased life span of linseed oil sleeper</th>
<th>+ 50% increased life span of linseed oil sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linseed oil sleeper (alt. 1)</td>
<td>146%</td>
<td>117%</td>
<td>97%</td>
</tr>
<tr>
<td>Linseed oil sleeper (alt. 2)</td>
<td>78%</td>
<td>63%</td>
<td>52%</td>
</tr>
<tr>
<td>Creosote sleeper</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
7 Conclusions and recommendations

- The results in this study indicate that the linseed oil sleepers have a lower footprint than creosote over its life cycle when considering ecotoxicity potential and human toxicity potential (considering carcinogenic substances). The main differences can be found in the production stage where emissions of organic pollutants in the creosote production contribute to the toxicity footprint. These emissions do not occur in the linseed production system.
- The linseed oil sleepers have a similar or lower footprint than creosote over its life cycle, as indicated in this study, when considering human toxicity potential (non-carcinogenic substances) and non-renewable primary energy. During the linseed cultivation, fossil energy is consumed in trucks and tractors, while the raw material for creosote is of fossil origin. Depending on the allocation method, the results can be either similar or better for the linseed oil sleeper in comparison to the creosote sleeper.
- As indicated in the results of this study, the linseed oil sleepers have a similar or higher carbon footprint than creosote over its life cycle. The main contribution to the carbon footprint of the linseed oil sleeper is the linseed cultivation.
- By reusing the sleeper after its use phase or increasing the life span, the linseed oil sleeper may have a lower carbon footprint than the creosote sleeper.
- To decrease the carbon footprint of linseed oil production, which is the main contributor to the sleeper’s footprint, it is possible to:
  - Decrease and optimise the use of linseed oil per sleeper, considering of course that the expected life span and material properties do not change.
  - Increase the value of by-products along the life cycle, resulting in a lower burden associated to linseed and linseed oil.
  - Change the fossil fuels (diesel and natural gas) to renewable fuels, such as HVO or FAME, resulting in a lower footprint for the linseed cultivation and linseed oil production.
- According to this study, the results indicate that the environmental footprint of a linseed oil sleeper varies to a large extent depending on which allocation method is used to allocate between linseed, straw, linseed oil and linseed cake. The prices of these products may vary from year to year depending on availability and demand, which may affect the results. Allocation based on mass will most likely not vary from year to year like an economic allocation.
- A few environmental impact categories were selected to be analysed within this study, meaning that other possible environmental concerns may not be investigated here. For example, freshwater eutrophication and particle emissions.
- As a final remark, this LCA study is performed in an early stage of product development and the data used in this study is based on the knowledge and processes available today. In a future scenario, the production processes may look different than today depending, for example, on implementation of environmental policies and new and enhanced knowledge on the studied product systems.
8 References


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