Preliminary environmental impact assessment of plant-based oils as fossil-based bitumen alternatives based on Dutch Environmental Cost Indicator (ECI) scoring method

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ABSTRACT: This study serves as a preliminary environmental impact assessment of 10 plant-based oils to substitute fossil-based bitumen used in road construction in the Netherlands using life cycle assessment based on EN 15804 +A1 and the CML midpoint impact category method, where the outcome is monetized using the environmental cost indicator (ECI) score governing in the Netherlands. Inventories of the products are obtained from the combination of available databases (EcoInvent and Agri Footprint 5) and existing research papers. The outcome shows that excluding the biogenic carbon dioxide storage capacity in the bio-based feedstocks causes their ECI scores per 1 ton of material as the functional unit to be higher than the fossil-based bitumen, with the exception of used cooking oil, when compared with bitumen from the EcoInvent database (€52 vs €94.1/ ton). Including biogenic carbon storage leads to the materials cooking oil, tall oil pitch and rosin scoring lower than bitumen (-€95.4 and -€91.2/ton). The total scores are dominated by the human toxicity, marine aquatic eco-toxicity, and global warming potential impact categories. Thus, the feedstocks with the lowest total ECI scores are used cooking oil, tall oil pitch, and tall oil rosin.

1 INTRODUCTION

In the construction industry, bitumen is widely used as a binder component in a bituminous mix for road structures as an alternative to cementitious materials. There has been a growing concern over time about the environmental impact of fossil-based bitumen usage, where its production consumes an enormous amount of energy of about 0.33 GJ/ton in the Netherlands (Oliveira & Silva, 2022) with the carbon footprint intensity recorded at 53.7 kg CO2-eq/ton, one-four of the annual emission of a one-person vehicle (Shacat et al., 2024). Therefore, alternative bio-binder materials have been proposed throughout the years.

The application of bio-based materials in road construction has been popular in recent decades. The application of the bio-binder constituents yields mixed outcomes in terms of performance. Most oil seeds, including linseed, rapeseed, castor and soybean oils are reported to increase the penetration and decrease the softening point of the binder mix, leading to a softer binder with marginal rutting resistance. Meanwhile, corn oil enhances rutting resistance and viscosity but also increase cracking and moisture susceptibilities, and tall oil resin produces a more resistant material at high and low temperatures. In addition, waste cooking oil is often reported to act as a rejuvenator owing to its psycho-chemical composition, which allows it to soften aged bitumen (Awogbemi et al., 2019; da Silva et al., 2022; Quan et al., 2024). This study intends to evaluate the environmental impact of 10 bio-based materials to substitute the fossil-based bitumen in the Dutch context based on the preliminary research conducted in the CircuRoad consortium, a knowledge-based group in the Netherlands established to support the national goal of reaching net-zero carbon state in 2050. The products analysed herein are castor oil, Jatropha oil, linseed oil, rapeseed oil, corn oil, soybean oil, tall oil pitch, tall oil rosin, tall oil rosin ester, and used cooking oil.

2 METHOD

2.1 *Goal and Scope*

This study contains the outcome of the screening-phase life cycle assessment (LCA) to provide a preliminary comparison of the environmental impact of the 10 plant-based oils considered to replace fossil-based bitumen. The list of materials is based on their technical performance and compatibility in the asphaltic mixture and availability in the Netherlands, as provided by the preliminary literature study conducted within the CircuRoad consortium. The current scope of this report is the **cradle-to-production gate** of each constituent, which accounts for the **A1 stage only**. The functional unit used in this stage is **1 ton of binder materials used in the asphalt mixture for road construction**. The geographical scope in this study is the Netherlands. However, the inventory data is taken from the country from which the material is exported to the Netherlands according to World Bank database (*freely accessible from* https://wits.worldbank.org/trade/comtrade/en/country/NLD/year/2023/tradeflow/Imports/partner/ALL/product/150790).

2.2 *Inventory*

The inventory data combines the generic databases of EcoInvent and Agri Footprint 5 (which are available directly in SimaPro) and research papers. In general, there are two available streamlines for the plant-based oils. Firstly, the oil can be considered a co-product in the system, where the whole impact is calculated from the cultivation activities at farm. There are some extra steps included in several materials, such as drying of rapeseed and maize grain, steeping and de-germ processing of wet maize grain, and retting and scutching for linseed oil. On the other hand, tall oil and used cooking oil are considered waste product, where their system boundary exclude the impact from the stages prior to the first processing stage at the plant, which is part of the cut-off principle applied in the Eurocode.

The biogenic carbon dioxide content of each material is taken either from the existing information in the database or calculated based on EN 16449 about the calculation rule of biogenic carbon content in plant-based product and conversion to carbon dioxide. Moreover, only mass allocation is considered in this study, as preferred in the Eurocode to deal with multifunctionality issue.

Lastly, the transportation distance from the farm to the extraction plant is assumed to be 50km for each case.

2.3 *Impact Assessment*

In this phase, all relevant inventories from the reference flow adjusted to the functional unit are grouped and converted according to the impact categories associated with each item in the list. The EN 15804 +A1 norm specifies the CML 2001 midpoint method to be used in the impact assessment, which generates 11 impact categories. Furthermore, the outcome will be weighted using the environmental cost indicator system developed in the Netherlands to describe the shadow cost from the environmental impacts, known as the Environmental Cost Indicator (ECI, or *Milieukosten Indicator* – MKI in Dutch). The conversion factors to the ECI score are governing for all impact categories from the CML method, and are given in (CE Delft, 2020). However, the ECI score does not contain a specific value to account for the biogenic carbon dioxide intake, since the global warming potential impact category includes the total of biogenic carbon intake (usually taken into account with negative characterization factor) and other types of greenhouse gases (usually with positive factor).

3 RESULTS AND DISCUSSION

3.1 *ECI score of bio-based oils*

The total ECI scores for all of the evaluated materials according to EN 15804 +A1 are shown in Figure *1*.

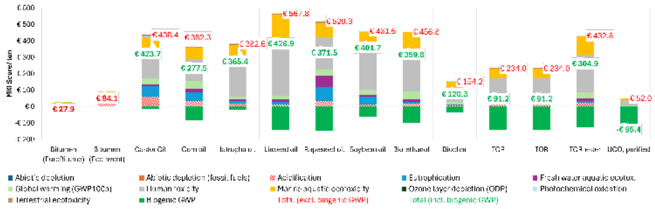

Figure 1. Total ECI score (including vs excluding biogenic CO_2 uptake) of the evaluated bio-based oils

Upon excluding the biogenic carbon dioxide uptake (numbers given in black), it is evident from (numbers are written in black, whereas the baseline – bitumen is written in red) that given the ECI scoring system based on EN 15804 +A1, three impact categories become the primary contributors in general. The most significant factor herein is **human toxicity (HTP),** with a relative contribution of 40 – 60% of total ECI scores in all the materials. The second most influential impact category is **marine aquatic eco-toxicity** potential **(MAETP)**, with the relative contribution ranging from 17 – 40% for all materials. Lastly, **global warming potential (GWP)** is considered a significant impact category with the relative contribution ranging from 5 – 22% for 12 materials, excluding castor oil, soybean oil, rapeseed oil, and jatropha oil.

Finally, when excluding the biogenic climate change impact, it is apparent that **linseed oil** yields the highest score by €567.8/ ton oil. The ECI score of bitumen from the Eurobitume inventory **(€28/ton)** is evidently lower than all the evaluated alternatives, whereas only the purified used cooking oil yields a lower score than the bitumen derived from EcoInvent database **(€94.1/ton)**. Comparing the score of bitumen with that of Kraft lignin used in another bio-binder study in the Netherlands also shows that the lignin product produced using the energy from natural gas will yield the score of €250/ ton, placing it in the middle position of the list (Moretti et al., 2022). However, including the effect of biogenic carbon dioxide uptake will change the outcome (numbers given in green), where both tall oil pitch and rosin also have lower ECI scores than bitumen (EcoInvent). Hence, the three products with the lowest ECI scores are **purified used cooking oil (€52 and -€95.4/ton), tall oil pitch, and tall oil rosin (€234 and €91.2/ton)**.

3.2 *Process contribution for three most dominant impact categories*

The contribution of each production stage of the evaluated materials associated with the three most dominant impact categories based on the ECI score is illustrated in *Figure 2*.

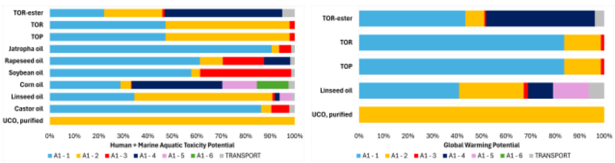

Figure 2. Process contribution associated with (left) human toxicity and (right) global warming potential

The first production phase (**A1 – 1**) is the primary contributor to the toxicity categories in 4 materials, such as jatropha oil, rapeseed oil, soybean oil, and castor oil, all of which resemble the cultivation stage of these materials. Among all the inputs in this phase, the **use of fertiliser** and **agricultural activities**, i.e. harvesting and ploughing, which introduce diesel fuel consumption, are the common causes of this impact. Both the impact from agricultural activities and urea fertiliser are derived from the production of the machineries, which utilizes coke derived from coal. The production of coke is found to emits carcinogenic compounds such as cadmium and arsenic (Institute, n.d.). The phosphate fertiliser production in the plant potentially emits heavy metal compounds, such as lead and cadmium, that leech to the aquatic environment and pose significant harm to it (Noli et al., 2024).

The second production stage (**A1 – 2**) is the main contributor to the toxicity impacts of linseed oil, used cooking oil, and tall oil products. Both the coke derived from coal production to **produce the infrastructure for the electricity** and **natural gas** supply to derive the energy and equipment for **retting and extraction** activities of the linseed oil and used cooking oil production chains. Lastly, the **crude tall oil production** involves sulfuric acid. The production of sulfur emits toxic substances such as sulfur dioxide and benzene, which become the major cause of human toxicity potential due to its ability to induce potential breathing issue that can be lethal (Agency for Toxic Substances and Disease Registry, n.d.)

Other two classifications of production processes (**A1 – 3 and A1 – 4**) are the major factors for corn oil and tall oil rosin ester. In the corn oil production, coke production involved in the infrastructure process to produce electricity is the major factor for the **drying** activity**.** Meanwhile, pentaerythritol, an alcohol substance commonly employed in the **esterification process** in tall oil rosin ester (TOR-ester) manufacturing, is synthesised from formaldehyde, the substance that becomes the main driver of the human toxicity potential score herein.

In summary, both the **coke production involved in the infrastructure process** related to energy source production (natural gas) or equipment that emits carcinogenic compounds, and the formaldehyde emission from the alcohol compound production used in the esterification process are the major factors in the toxicity impact categories. The relationship between coke and infrastructure in this case is mostly that coke is used in the steel manufacturing, where the steel is used to construct supporting infrastructures, such as pipeline for natural gas transmission, agricultural machinery, or furnace.

Lastly, the global warming potential generally stems both from the greenhouse gas emissions directly recorded during the cultivation practices (**A1 – 1**) and indirect emissions from the of energy sources generation, such as natural gas or heavy fuel, used in the oil production processes. The natural gas production process emits an enormous amount of methane.

Based on the preliminary LCA conducted in this study, it is evident that toxicity impacts become the primary concern in the outcome. This circumstance even occurs despite a relatively low ECI weighing factor given to those categories, all below 10 cents/ kg of impact category. Such phenomena have been previously reported as part of uncertainties, where the fate of substances contributing to the impact categories are considered infinite. Conversely, other impact categories, such as global warming potential, commonly consider 100 years as its fate, yielding a difference in the outcome (Frischknecht et al., 2007). However, this method has not accounted for land use, which is a critical factor for plant-based products. While EN 15804 +A2 has attempted to cover this aspect, an updated ECI value also needs to be established to adapt with the updated Eurocode. Moreover, since this analysis has been primarily carried out using generic database as the input (taking into account various geographical and temporal scopes for each), it will increase the uncertainty of the outcome. Hence, more extensive research needs to be conducted to produce the outcome more relevant to the scope of the Netherlands using primary and updated data. Lastly, while comparison can be made within this scope, a cradle-to-grave analysis needs to be performed furthermore to take into account the effect of incorporating the alternative materials into the asphalt mixture, which might result in different properties and durability compared with the conventional mixture made of fossil bitumen.

4 CONCLUSION

This study aims to compare the environmental impact of 10 plant-based oils as alternatives to replace fossil-based bitumen for road construction in the Netherlands. The evaluation is carried out using the CML midpoint impact category method in accordance with EN 15804 +A1, and weighted using the Environmental Cost Indicator (ECI) factors developed in the Netherlands to describe the shadow environmental cost of the oil products. Evidently, the cost of all plant oils exceed the fossil bitumen (calculation based on Eurobitume inventory) when excluding the biogenic carbon dioxide uptake, ultimately for linseed oil. In contrast, only used cooking oil has a lower score than bitumen (calculation based on EcoInvent database). Tall oil pitch and rosin will also have lower ECI score than the baseline bitumen when taking into account the biogenic carbon dioxide storage. Three major impact categories herein are human toxicity, marine aquatic eco-toxicity, and global warming potential. The toxicity impacts can be traced back to the emission of toxic materials from the production of coke related to the supporting infrastructure, such as steel manufacturing used for the pipeline for natural gas distribution and agricultural machinery. Meanwhile, global warming potential is derived from the direct emission of greenhouse gases during the cultivation practice and indirect emission from the production of energy source for the production stage. Hence, the three materials with the lowest ECI scores are **purified used cooking oil, tall oil pitch, and tall oil rosin**, and they specifically have lower ECI scores than the standard bitumen when accounting for the biogenic carbon dioxide storage potential.

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