Leverbaarheid 7.3:
LCA rapport over de milieu-impact van de BREPLA materialen

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Contents

Functional unit, goal & scope

The functional unit is 1 demonstrator as produced within the project. For each demonstrator, biobased BrePLA materials are compared to alternative materials.

A cradle-to-gate perspective is considered, covering the product's life cycle from resource extraction (cradle) to the factory gate, i.e., before transport to the consumer. Scrap production and treatment thereof were not taken into account. Their impact is assumed to be negligible compared to the impact of the raw materials.

Demonstrator 1: serving tray

The demonstrator serving trays have a dimension of 31 x 26 cm. Production is possible through hand lay-up of vacuum-infusion. Since no suitable LCA data is available for the hand lay-up process, vacuum-infusion was selected. It was confirmed at the end of this study that the production process had little influence on the final environmental impacts: the used raw materials contribute the most. Further, it was assumed that the same amounts of epoxy and bio-epoxy are required for the production of the BrePLA demonstrators.

The BrePLA serving trays are compared to a commercial serving tray[1] made from melamine of 37 x 53 cm, corresponding with a mass of 0,67 kg. Rescaled to the dimensions of the BrePLA serving trays, a mass of 0,275 kg is obtained. A typical production method for melamine-based product is compression molding.

	BrePLA option 1	BrePLA option 2	Alternative
Knitted flax fabric	40,5 g	40,5 g	-
Woven flax fabric	-	21,5 g	-
(Bio-)epoxy resin	118,8 g	130,1 g	-
Melamine resin	-	-	275 g

Demonstrator 2: furniture stool

Two furniture demonstrators are produced in the BrePLA project: a stool and a step-stool, using the same biobased materials. The stool was selected as example for the LCA screening. The total surface area of this stool is 180 x 30 cm.

The stool is produced through pressing, laminating (into a sandwich panel) and folding. Since only data on the laminating process is available in de database, and it was confirmed at the end of this study that the production process had little influence on the final impacts (compared to the choice of materials), it was decided to model the process by laminating only.

A similar commercial stool would typically be made from wood, for example the Ikea VILTO[2], made from solid birch (2,03 kg) or ODDVAR, made from solid pine (2,46 kg). Hence, the demonstrator is first compared to these commercial stools, using two types of sawnwood.

[1] https://www.xxlhoreca.com/dienblad-horeca-melamine-laminaat-krasvrij-euronorm-530x370mm/1018589

[2] https://www.ikea.com/be/en/p/vilto-step-stool-black-40358747/,

The first type is processed hardwood from different trees (oak, birch and beech), originating from sustainable forestry in Europe (EU) and Canada (CA). The second type is processed softwood from parana pine, originating from the Brazil region (BR) and also produced through sustainable forestry. More details are included in the 'inventory data collection'.

However, because the demonstrator serves as a proof-of-concept, a comparison between a biobased and a fossil-based composite material may be more appropriate. Therefore, the BrePLA materials are also compared to self-reinforced PP, a composite version of regular PP.

The self-reinforced PP stool is produced from PP woven fabric, that is thermoformed into the desired shape. For the self-reinforced PP composite to obtain the same bending stiffness and bending strength as the BrePLA composites, a mass of 3,4 kg is required. More details on the calculation method can be found in the appendix.

	BrePLA option 1	BrePLA option 2	Alternative 1 (wood)	Alternative 1 (srPP)
PLA honeycomb core	0,59 kg	0,59 kg	-	-
PLA-film	0,47 kg	0,48 kg	-	-
Woven basalt fabric	0,95 kg	-	-	-
Woven flax fabric	-	0,54 kg	-	-
Sawnwood – EU/CA	-	-	2,03 kg	-
Sawnwood – BR	-	-	2,46 kg	-
Self-reinforced PP (srPP)	-	-	-	3,4 kg

<u>Demonstrator 3: car roofbox</u>

The dimensions of the BrePLA roofbox are 126 x 44 x 30 cm, corresponding with a mass of 15,9 kg. The production method is thermoforming.

A commercial roofbox can for example be made from PP, dimensions 131 x 78 x 38 cm, corresponding with mass of 11 kg[3]. Rescaling to the dimensions of the BrePLA demonstrator, taking also the difference in stiffness into account, results in a mass of 5,15 kg PP. More details on the calculation method can be found in the appendix. The production process is injection molding.

However, analogous to demonstrator 2, a comparison between biobased and fossil-based composite materials would be more appropriate, since the demonstrator serves as a proof-of-concept. Therefore, the biobased composite material is also compared to a carbon fiber- epoxy composite. A roofbox made from the latter with the same stiffness as the rescaled BrePLA roofbox and the commercial PP roofbox has a total mass of 2,28 kg. The chosen production process is low-pressure resin transfer moulding (LPRTM).

[3] https://www.renaultwebwinkel.nl/a-73838826/jogger/dacia-dakkoffer-480-liter/#description

	BrePLA material	Alternative 1	Alternative 2
Flax nonwoven	2,58 kg		-
PLA nonwoven	2,58 kg		-
PP (pellets)	-	4,71 kg	
Carbon fibre weave	-	-	1,26 kg
Epoxy resin	-	-	1,01 kg

Inventory data collection

The foreground system is the production of 1 demonstrator made from bio-based materials or current alternative materials. All upstream processes connected to this foreground system, i.e. the background system, are modelled with the Ecoinvent v3.6 database.

Material	Ecoinvent flow
Flax fiber	Fibre, flax {GLO}| market for fibre, flax | Cut-off, U
PLA polymer	Polylactide, granulate {GLO}| market for | cut-off, U
PP polymer	Polypropylene, granulate {GLO}| market for | cut-off, U
Epoxy resin	Epoxy resin, liquid {GLO}| market for | Cut-off, U (adapted to Sicomin)
Melamine resin	Melamine {GLO}| market for | Cut-off, U
Sawnwood 1 (EU-CA)	Sawnwood, board, hardwood, dried (u=10%), planed {GLO}| market for | Cut-off, U
Sawnwood 2 (BR)	Sawnwood, parana pine from sustainable forest management, kiln dried {GLO}| market for | Cut-off, U

In case of basalt fibres, bio-epoxy resin and carbon fibres, no Ecoinvent data was available. Existing studies with direct impact results were used for basalt fibres and bio-epoxy resin (see next section) while inventory data from Gopalraj et al.[4] was used to model the carbon fibres.

The first type of sawn wood is described as follows: "This product represents sawn hardwood which has been kiln or air dried to a water content of 10%. It is used as a construction material, a.o. for the production of wooden furniture." The wood originates from Europe and Canada (EU-CA) and consists of oak, beech and birch.

[4] *Gopalraj et al. (2021) Life Cycle Assessment of a Thermal Recycling Process as an Alternative to Existing CFRP and GFRP Composite Wastes Management Options. Polymers, 13(24), 4430*

The second type of sawnwood is parana pine softwood. It grows in Brazil (BR) and adjacent areas of Paraguay and Argentina. This Ecoivent flow provides no details about the product subcategory (board, beams or laths) or water content after kiln or air drying.

Modelling of textile structures (knitted fabrics, woven fabrics and nonwovens) was performed with an internal tool at Centexbel. The calculation is based on the electricity and water use required for the different processing steps: from extrusion (in case of thermoplastic polymers) and spinning (in case of staple fibres) to weaving, knitting or nonwoven production. The energy consumption is a function of the thickness of the fiber or yarn, expressed in tex.

Demonstrator n°	Fabric type and fiber/yarn thickness
demonstrator 1	knitted flax fabric (400 tex), woven flax fabric (83 tex)
demonstrator 2	woven flax fabric (83 tex), woven basalt fabric (150 tex)
demonstrator 3	nonwoven flax (83 tex), nonwoven PLA (24 tex), CF weave (568 tex[5])

The demonstrator production processes (vacuum infusion, compression moulding, injection moulding and laminating) were modelled through their respective energy use in terms of kwh electricity of MJ heat from natural gas.

Process	Modelling
vacuum infusion	0,284 kwh and 1,13 MJ per kg, based on the inventory of '*Vacuum infusion, rigid composites part, at plant/kg/RNA*'
injection molding	1,48 kwh and 4,21 MJ per kg, based on the inventory of '*Injection moulding {RER}| processing | Cut-off, U*'
compression moulding	average of 2,81 kwh per kg[6]
laminating	average of 4,17 kwh per kg[7]
thermoforming	0,71 kwh per kg, based on the inventory of '
LPRTM	2,85 kwh per kg[8]

Electricity, heat from natural gas and water use required for the processes above were modelled with the following Ecoinvent flows:

[5] *Average of Toray typical carbon fiber properties*

[6] *https://s3-eu-west-1.amazonaws.com/pstorage-acs6854636/9605389/es7b04069_si_001.pdf*

[7] *https://core.ac.uk/download/pdf/286425701.pdf*

[8] *Gopalraj et al. (2021) Life Cycle Assessment of a Thermal Recycling Process as an Alternative to Existing CFRP and GFRP Composite Wastes Management Options. Polymers, 13(24), 4430*

In/output	Ecoinvent flow
Electricity	Electricity, medium voltage {BE}| market for | cut-off, U
Heat	Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U
Demi water	Water, deionised {EU}| market for water, deionised | cut-off, U
Wastewater	Wastewater, average {EU}| market for wastewater, average | cut-off, U

Impact assessment

The next step is the aggregation of the inventory flows into environmental impacts, by multiplying them with specific characterization factors. This can be done at different levels, of which the midpoint category is the first one. The midpoint impacts can on their turn be aggregated into three endpoint categories (human health, ecosystems and resources) or one single score impact category.

Although a single score impact value is easier to understand for the broad audience, one must be with its interpretation, as for a lot of information can be lost or hidden due to the aggregation.

The impact assessment of this study is based on the International Life Cycle Data system (ILCD) method, as developed by the European Commission's Joint Research Centre (JRC). Besides the fact that this method is applied in the PEF (Product Environmental Footprint), an additional reason to choose this method was the study from VITO[9], in which the environmental impacts of basalt fibres (produced by Basaltex) are calculated through the ILCD. By also using the ILCD method in this study, it was easier to adopt the impact results of the basalt fibres.

In case of bio-epoxy however, the available impact data received from producer Sicomin is based on the CML method. To be able to use this data in combination with the ILCD results, conversion factors developed by Dong et al. (2021)[10] were applied.

For impacts without conversion factor or impacts present in ILCD but not in CML, values from regular epoxy resin were taken from the Ecoinvent database. This concerns the following impact results: Land use, Water use, Particulate matter, Ionizing radiation, Terrestrial and Marine eutrophication. Especially land and water use are important for bio-based materials and can cause an underestimation of the impact of bio-based epoxy resin.

[9] *Boonen, K.; Janssens, G.; Manshoven, S. (2017) Summary report on the environmental potential of basalt fibres versus glass fibres. Study accomplished under the authority of Basaltex NV.*

[10] *Dong, Y.; Hossain, M.U.; Li, H.; Liu, P. (2021) Developing Conversion Factors of LCIA Methods for Comparison of LCA Results in the Construction Sector. Sustainability 13, 9016.*

Demonstrator 1 results

The absolute midpoint impact results are given in the table below:

Impact category	unit	flax knit bio-epoxy	flax knit epoxy	flax knit flax weave bio-epoxy	flax knit flax weave epoxy	melamine
Climate change	kg CO2 eq	0,72	1,20	1,01	1,49	1,44
Ozone depletion	kg CFC-11 eq	1,4E-08	3,0E-08	1,7E-08	3,3E-08	2,2E-07
Human toxicity	Ctuh	-1,6E-07	-1,6E-07	-2,6E-07	-2,5E-07	6,5E-08
Particulate matter*	kg PM2.5 eq	6,3E-05	6,3E-05	9,7E-05	9,7E-05	2,2E-03
Ionizing radiation HH*	kBq U235 eq	2,4E-02	2,4E-02	2,8E-02	2,8E-02	1,3E-01
Ionizing radiation E*	CTUe	1,9E-07	1,9E-07	2,2E-07	2,2E-07	1,0E-06
Ozone formation	kg NMVOC eq	1,6E-02	6,3E-02	1,6E-02	6,4E-02	2,7E-03
Acidification	molc H+ eq	5,9E-03	8,0E-03	6,7E-03	8,9E-03	1,0E-02
Terrestrial eutrophication*	molc N eq	1,1E-02	1,1E-02	1,5E-02	1,5E-02	3,3E-02
Freshwater eutrophication	kg P eq	2,5E-04	1,3E-04	2,5E-04	1,4E-04	1,7E-05
Marine eutrophication*	kg N eq	1,3E-03	1,3E-03	1,8E-03	1,8E-03	1,0E-03
Freshwater ecotoxicity	CTUe	4,4E-01	5,6E-01	6,7E-01	7,9E-01	1,1E+00
Land use*	kg C deficit	7,9E-01	7,9E-01	1,2E+00	1,2E+00	1,9E-01
Water use*	m3 water eq	3,0E-02	3,0E-02	4,6E-02	4,6E-02	7,8E-03
Resource depletion	kg Sb eq	4,9E-06	1,5E-05	5,4E-06	1,5E-05	3,9E-06
Single Score	mPt	**0,09**	**0,17**	**0,12**	**0,20**	**0,33**

*HH = Human Health, E = Ecosystem, * = impacts from regular epoxy that are used for bio-epoxy*

Below, these results are presented with a radar plot, allowing to visualize multiple data with different quantitative scales together. Each impact is expressed as a fraction of the highest impact value (within the same impact category).

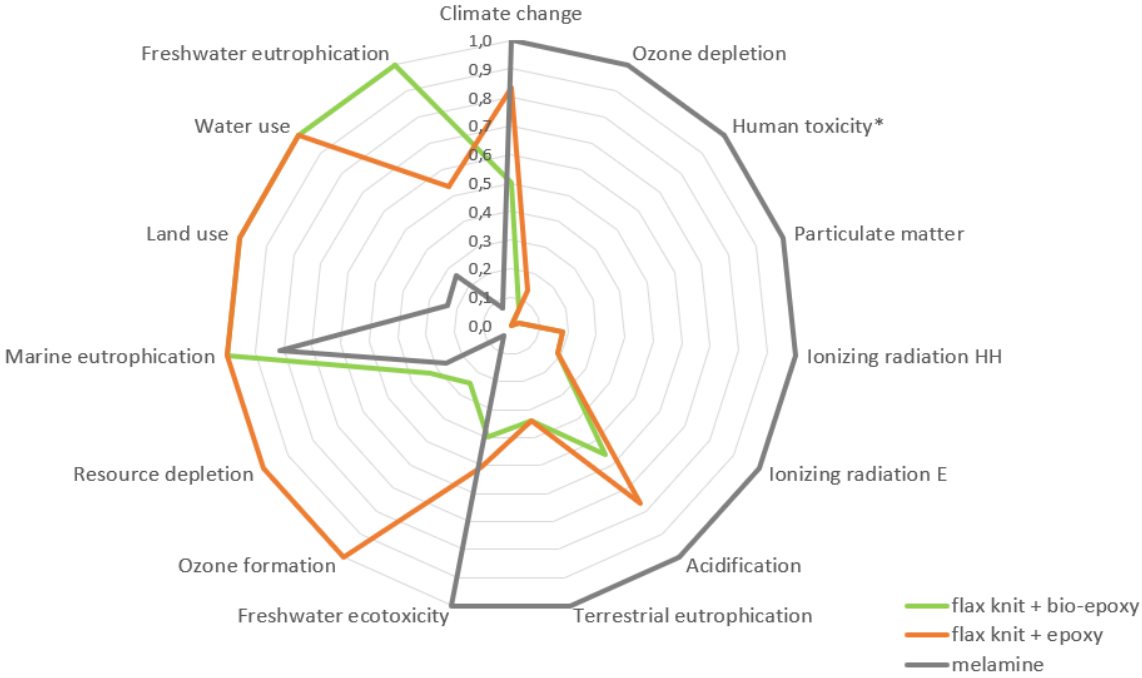
<u>BrePLA option 1 vs. alternative</u>

The alternative tray made from melamine has the highest impacts for climate change, ozone depletion, human toxicity, particulate matter, ionizing radiation (both human health and ecosystems), terrestrial eutrophication, freshwater ecotoxicity and acidification.

The tray made from a flax knit + regular epoxy has the highest impact scores for resource depletion, ozone formation, land use, water use and marine eutrophication. The latter three are related to flax cultivation. Resource depletion is largely due to epoxy production. One can argue that there is a shift in impacts from the right side of the graph to the left side.

Finally, the flax knit + bio-epoxy tray has the highest impact scores for freshwater eutrophication, land use, water use and marine eutrophication. It is important to note that the last 3 are the same as for regular epoxy because these values were taken directly, due to lack of data for bio-epoxy.

Since bio-epoxy is derived from plants, we expect in reality higher impacts for land use and water use, compared to regular epoxy. Nonetheless, even with aforementioned higher impacts, the tray made from knitted flax and bio-epoxy seems to be the most favourable scenario.



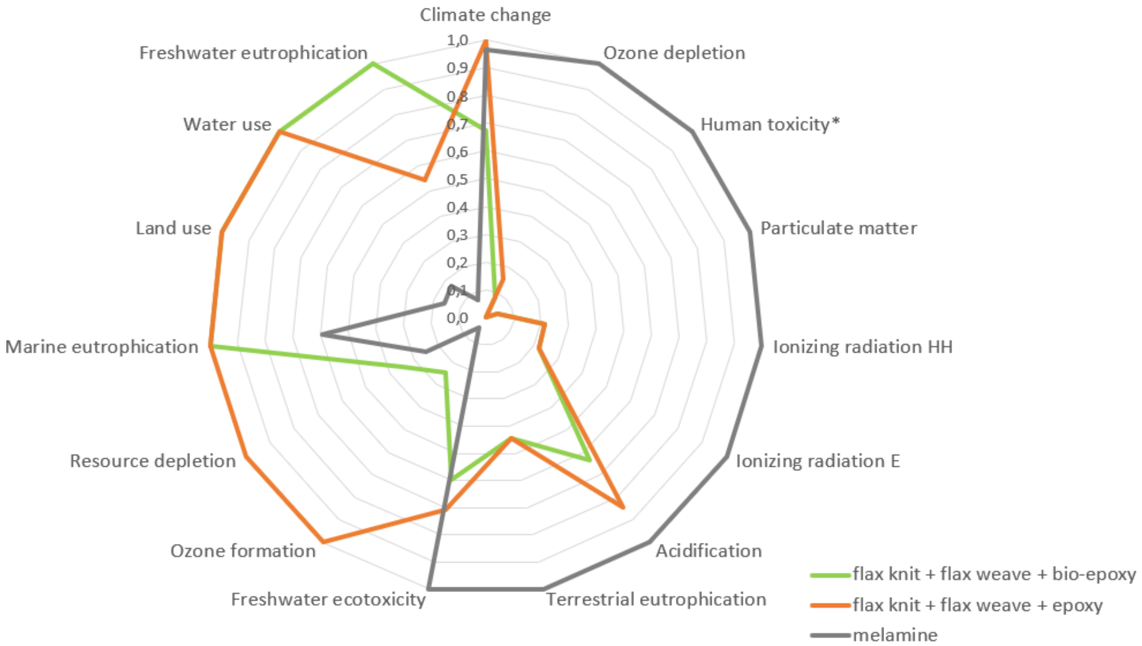
<u>BrePLA option 2 vs. alternative</u>

The serving tray made from melamine still has the highest impact values for ozone depletion, human toxicity, particulate matter, ionizing radiation, acidification, terrestrial eutrophication and freshwater ecotoxicity.

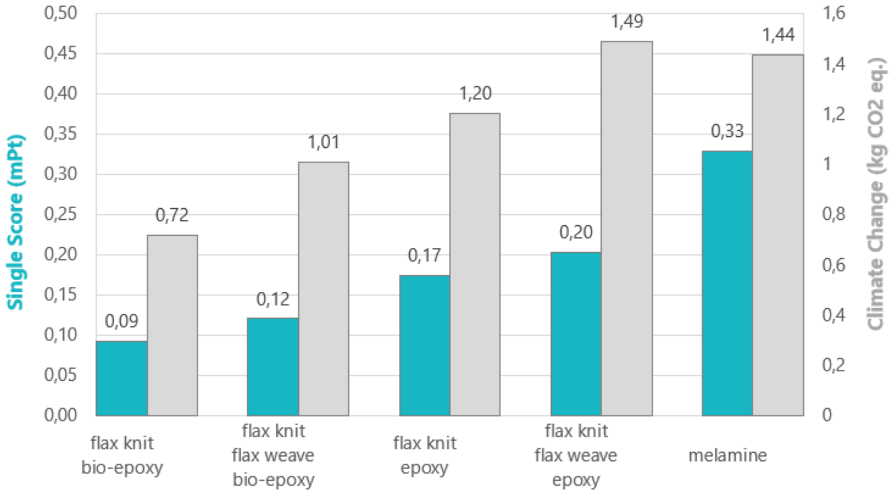
However, the Climate Change impact of the flax knit-weave + epoxy combination (1,49 kg CO2 eq.) is a bit higher than impact of melamine (1,44 kg CO2 eq.). This is because weaving is much more energy intensive than knitting, and the energy consumption increases with decreasing fiber diameter. This higher electricity use has caused an increase in Climate Change impact.

Further, the flax knit-weave + epoxy composite has the highest impact scores for ozone formation, resource depletion, land use, water use and marine eutrophication, similar as in option 1.

The flax knit-weave + bio-epoxy composite has the highest impact scores for land use, water use, freshwater eutrophication and marine eutrophication, which is again similar as in option 1.



The final step is the calculation of the single score impact results. They are presented together with the Climate Change results, because this is the most well-known and applied impact category, although focussing only on this impact category would lead to different conclusions. It is therefore of importance to take the other impact categories also into consideration, both at individual level as done above, and at aggregated single score level.



Conclusions for demonstrator 1:

- The most favourable option is the flax knit + bio-epoxy composite, if it performs technically as well as the flax knit-weave + bio-epoxy composite. This is because of the much more energy intensive weaving process, compared to knitting. A greener electricity mix could help reduce the high impacts of the weaving process.
- With respect to Climate Change only, the flax knit-weave + epoxy composite scores quasi equally bad as melamine. The use of flax cannot compensate for the CO_2 contributions coming from weaving and epoxy production. However, when looking at the aggregated single score, melamine has a higher value (0,33 mPt) than the flax knit-weave + epoxy (0,20 mPt). Also at

individual midpoint impact level, presented with the radar plots, more environmental benefits are clearly visible.

Demonstrator 2 results

The absolute midpoint impact results are shown in the table below:

Impact category	unit	Option 1 PLA-basalt	Option 2 PLA-flax	Sawn wood EU-CA	Sawn wood BR	srPP
Climate change	kg CO2 eq	7,49	6,19	25,28	0,38	2,63
Ozone depletion	kg CFC-11 eq	1,3E-06	9,5E-07	3,7E-06	4,2E-08	3,2E-07
Human toxicity NC	Ctuh	8,0E-07	-2,2E-06	1,2E-06	1,4E-07	1,5E-07
Human toxicity C	CTuh	1,3E-07	5,2E-07	9,6E-08	2,0E-09	5,3E-09
Particulate matter	kg PM2.5 eq	2,8E-03	3,1E-03	7,6E-03	1,7E-03	9,4E-03
Ionizing radiation HH	kBq U235 eq	1,9E+00	1,2E+00	5,3E+00	2,3E-02	1,4E-01
Ionizing radiation E	CTUe	1,3E-05	9,1E-06	4,2E-05	1,8E-07	1,1E-06
Ozone formation	kg NMVOC eq	1,8E-02	1,9E-02	6,3E-02	3,8E-03	1,2E-01
Acidification	molc H+ eq	3,2E-02	4,5E-02	7,7E-02	2,9E-03	1,9E-02
Terrestrial eutrophication	molc N eq	9,4E-02	1,6E-01	1,8E-01	1,1E-02	6,6E-02
Freshwater eutrophication	kg P eq	1,2E-03	5,4E-04	5,4E-04	5,0E-05	8,4E-05
Marine eutrophication	kg N eq	1,0E-02	2,0E-02	1,6E-02	1,0E-03	6,0E-03
Freshwater ecotoxicity	CTUe	2,1E+01	1,9E+01	6,6E+00	4,8E-01	8,6E-01
Land use	kg C deficit	9,1E+00	1,7E+01	9,1E+00	2,8E+01	7,9E+01
Water use	m3 water eq	1,0E-01	4,8E-01	5,5E-02	1,7E-04	< 0
Resource depletion	kg Sb eq	5,5E-05	5,0E-05	2,2E-04	7,7E-07	2,8E-06
Single Score	mPt	2,29	4,21	3,40	0,13	0,54

NC = non-cancer, C = cancer, HH = Human Health, E = Ecosystem, EU-CA = Europe & Canada, BR = Brasil

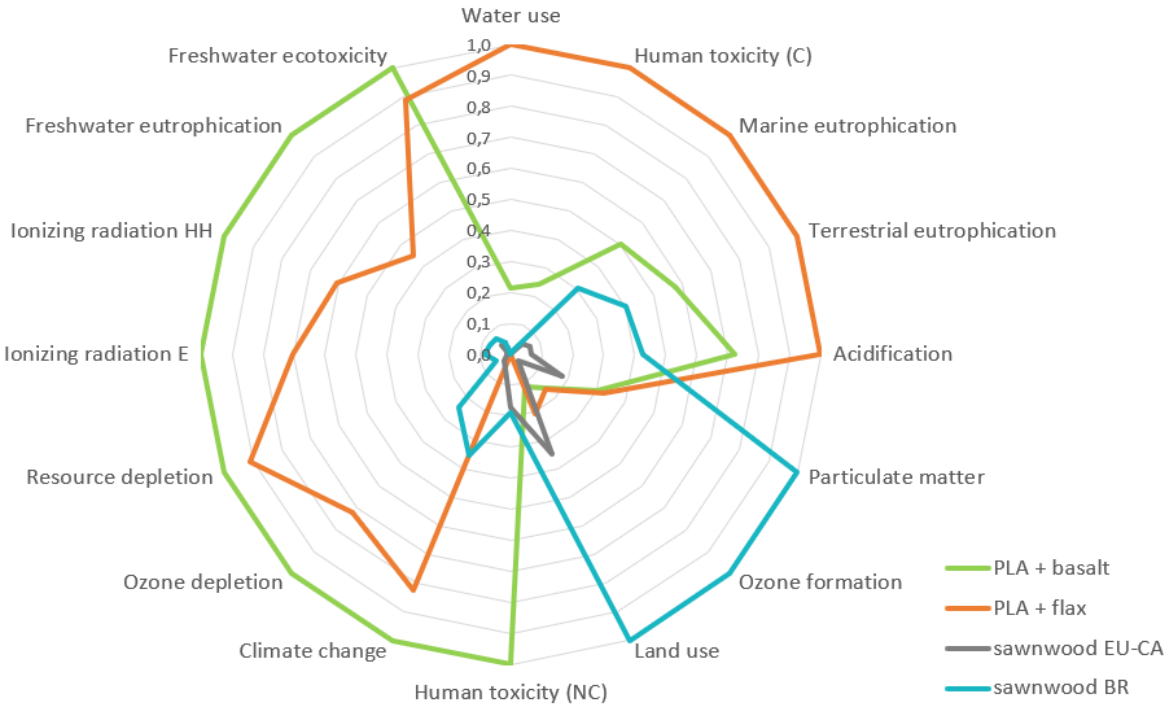
Below, the results are again presented with a radar plot, allowing to visualize multiple data with different quantitative scales together. Each impact is expressed as a fraction of the highest impact value (within the same impact category).

<u>BrePLA option 1 and 2 vs. wood</u>

The basalt-PLA and flax-PLA composites have higher impacts than sawnwood, expect for the impact categories land use - which is of course much larger for timber production - ozone formation and particulate matter, the latter two only in case of sawnwood from Brasil. These two impact categories are related to transport for import and the use of forest machinery (e.g. less sustainable fuels and green energy compared to sawnwood production in Canada and Europe).

Both sawnwood types, from both Europe/Canada and Brasil, involve sustainable forest management, meaning that the harvests remove no more wood than is grown, i.e., if the landscape-level forest inventory is not declining over time. This allows a meaningful environmental assessment of a wood-based product.[11]

In addition, flax-PLA composites have a very low human toxicity (non-cancer) impact compared to the all the other materials.



<u>BrePLA option 1 and 2 vs. srPP</u>

The self-reinforced PP alternative has the highest impact scores for human toxicity (non-cancer), ozone depletion, ionizing radiation, resource depletion, climate change, particulate matter, ozone formation, acidification and terrestrial eutrophication.

For the PLA-flax composite, the impacts are shifted towards marine eutrophication, land use, water use and human toxicity (cancer). These are related to cultivation of crops for both flax and PLA. Cultivation involves not only land occupation but also fertilisation, which is reflected by the toxicity and eutrophication impacts

The PLA-basalt flax composite clearly has the lowest impact scores in each impact category, apart from freshwater eutrophication and freshwater ecotoxicity. Based on literature, a possible explanation is the release of particles during mining and high heath treatments in industrial furnaces. Basalt rocks contains metals like lead, zinc, cadmium and arsenic.[12]

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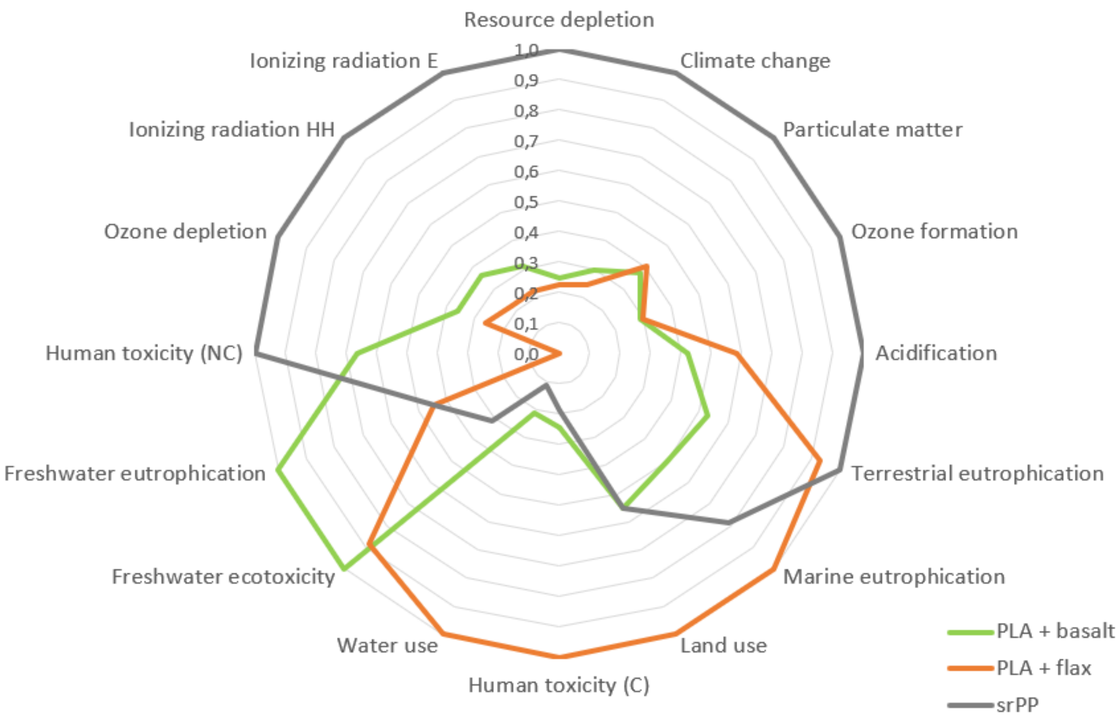
[11] Sarthre, R.; Gonzales-Garcia, S. (2014) Life cycle assessment (LCA) of wood-based building materials. In 'Eco-efficient construction and building materials', Woodhead Publishing Limited.

[12] https://www.negemproject.eu/wp-content/uploads/2022/06/NEGEM_D1.5_Sustainability-assessment-of-Geoengineering-NETPs.pdf



Conclusions for demonstrator 2

- Relative to rPP
  - When considering the impact on Climate Change only, large gains can be obtained by moving on to PLA-flax (↓ 70%) and PLA-basalt composites (↓ 75%).
  - When considering the single score, PLA-basalt is the most favourable bio-based option, with a value of 2,3 mPt compared to 3,4 mPt for srPP and 4,2 mPt for flax-PLA. This is also reflected in the radar plots, visualizing each impact category separately.
  - The single score impact also reveals that flax-PLA composites have a higher total impact compared to the alternative srPP composites. The impacts contributing to this high single score value are all related to crop cultivation: not only with respect to land and water use but also the use of fertilizers, fuel for agricultural machinery, etc. This leads to the conclusion that the flax-PLA composites might be more suitable to substitute other types of composites, for example epoxy reinforced with carbon fibers. For this reason, the choice was made to consider a carbon fiber epoxy composite in demonstrator 3.
- Relative to wood
  - No environmental gains could be obtained with respect to Climate Change and the Single Score impact when comparing to wood products.
  - Wood does have a much higher impact in land use, even for sustainable foresting. When considering sawnwood from Brasil (parana pine) instead of sawnwood from Europe and Canada (oak, birch, beech), there are also higher impacts linked to particulate matter and ozone formation.

Demonstrator 3 results

The absolute midpoint impact results are shown in the table below:

Impact category	unit	flax-PLA nonwoven	injection molded PP	carbon fibres + epoxy
Climate change	kg CO2 eq	16,17	46,89	44,26
Ozone depletion	kg CFC-11 eq	1,72E-06	1,49E-06	2,39E-05
Human toxicity NC	Ctuh	< 0	1,24E-06	1,63E-06
Human toxicity C	CTuh	2,64E-06	1,03E-07	9,61E-08
Particulate matter	kg PM2.5 eq	1,04E-02	2,10E-04	1,86E-02
Ionizing radiation HH	kBq U235 eq	1,69E+00	1,42E+00	3,91E+00
Ionizing radiation E	CTUe	1,32E-05	1,13E-05	3,27E-05
Ozone formation	kg NMVOC eq	5,95E-02	2,50E+00	1,93E+00
Acidification	molc H+ eq	1,71E-01	2,62E-01	1,33E+00
Terrestrial eutrophication	molc N eq	6,62E-01	1,99E-01	6,91E+00
Freshwater eutrophication	kg P eq	1,67E-03	5,01E-03	2,38E-03
Marine eutrophication	kg N eq	8,36E-02	1,80E-02	6,31E-01
Freshwater ecotoxicity	CTUe	6,57E+01	6,39E+00	5,22E+00
Land use	kg C deficit	6,81E+01	4,84E+00	5,52E+00
Water use	m3 water eq	2,37E+00	1,14E-02	1,12E-01
Resource depletion	kg Sb eq	1,31E-04	5,65E-04	2,07E-04
Single Score	mPt	19,21	6,42	12,00

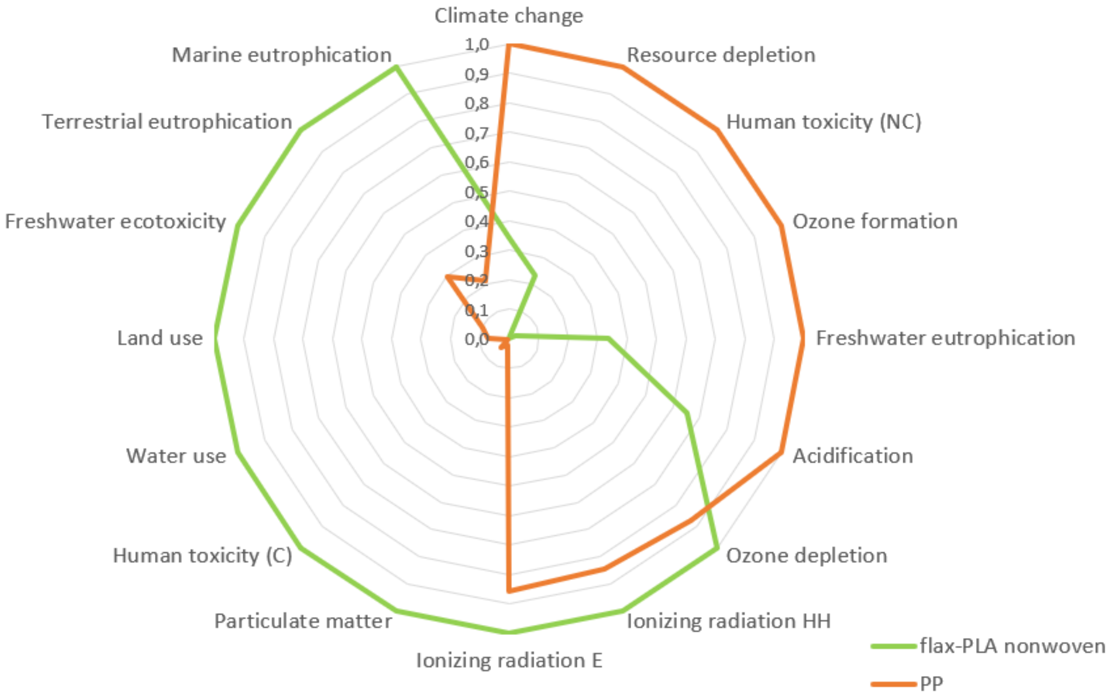
NC = non-cancer, C = cancer, HH = Human Health, E = Ecosystem

Below, the results are presented with a radar plot. Each impact is expressed as a fraction of the highest impact value (within the same impact category).

<u>BrePLA composite vs. injection molded PP</u>

A roofbox made from injection molded PP has a higher impact on Climate Change (46,89 kg CO2 eq.) than a roofbox made from the flax-PLA composite (16,17 kg CO2 eq.). The Single Score however, aggregating all the impact categories together, is higher for the flax-PLA composite (19,21 mPt) than for injection molded PP (6,42 mPt).

The radar plots show how the individual impacts are distributed. While PP has high impact scores for climate change, resource Depletion, human toxicity (NC), ozone formation, freshwater eutrophication and acidification, the flax-PLA composite has high environmental impacts for all the remaining impact categories.



<u>BrePLA composite vs. carbon fiber-epoxy composite</u>

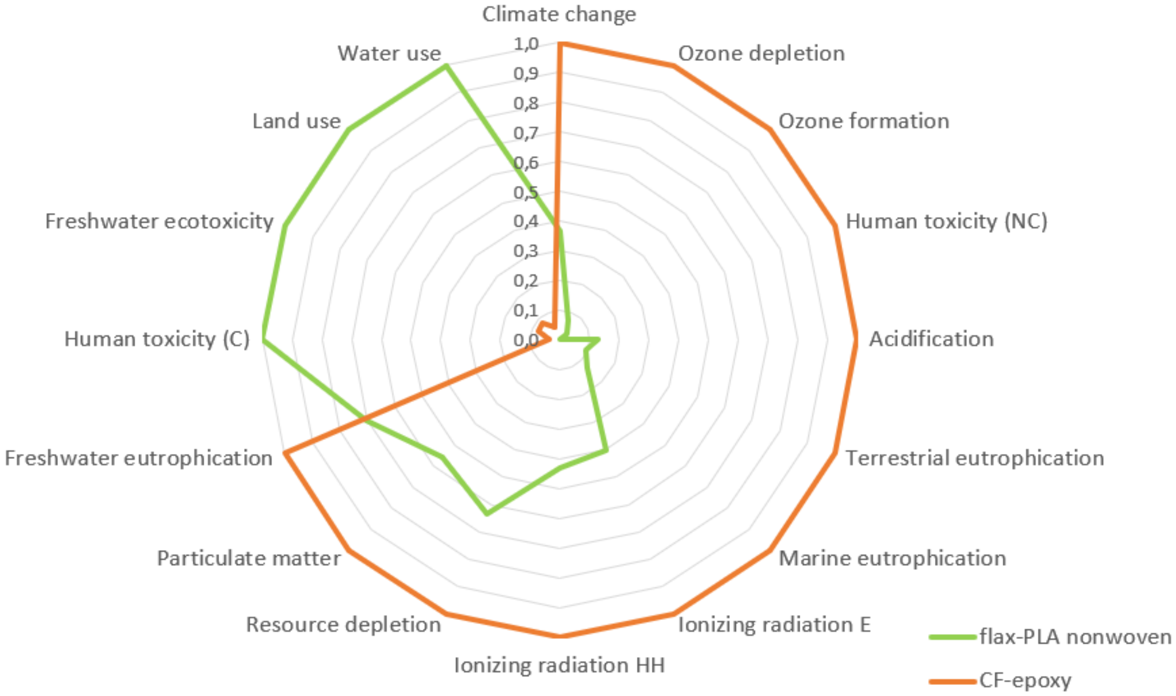
When contrasting the flax-PLA composite with the carbon fiber-epoxy composite, the environmental benefits are much larger (compared to PP as alternative material). The only impact categories for which flax-PLA has higher scores, are land use, water use, freshwater ecotoxicity and human toxicity, which are typical impacts related to crop cultivation.

For all the other impact categories, there is a significant decrease in environmental impact. In case of Climate Change for example, the value is reduced with 63%.

The higher impacts of land use, water use, freshwater ecotoxicity and human toxicity however still weigh into the single score of the flax-PLA composite, resulting in a value of 19,21 mPt compared to 12 mPt for the carbon fiber-epoxy composite.

Possible ways to anticipate this is further optimization of flax-PLA composite in the future, so less material is required to obtain the same stiffness criteria (which would lead to an overall reduction of the impacts), as well as a study of the potential end-of-life benefits of flax-PLA composites compared to carbon-fiber epoxy composites.

Nonetheless, the difference between the two alternatives, injection molded PP and CF-epoxy, shows the importance of considering which material the biobased composites are about to replace: from an environmental perspective, a much higher benefit can be obtained when used in a product that is normally made from CF-epoxy instead of one made from injection-molded PP.


Climate change
Ozone depletion
Ozone formation
Human toxicity (NC)
Acidification
Terrestrial eutrophication
Marine eutrophication
Ionizing radiation E
Ionizing radiation HH
Resource depletion
Particulate matter
Freshwater eutrophication
Human toxicity (C)
Freshwater ecotoxicity
Land use
Water use
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
flax-PLA nonwoven
CF-epoxy

Appendix

Additional data for the serving tray

Density melamine[13] = 1,14 g/cm³

Additional data and calculations for the stool

Density of hardwood (water content 10%)[14] = 614 kg/m³

Density of parana pine softwood, air-dried[15] = 545 kg/m³

The weight of the SR-PP stool is based on calculations with ElamX-software, where principles of the classical lamination theory are used, to reach at least the same bending strength in comparison to a flax-PLA (with 1 mm skin) and basalt-PLA (with 0.5 mm skin) sandwich panel with a 10 mm thick PLA core.

Assumed properties for:

SR-PP in 0° - & 90° - direction:

Tensile stiffness E = 3,1 GPa ; Tensile strength σ = 145 MPa.

Flax-PLA skins in 0° - & 90° - direction:

Tensile stiffness E = 13,2 GPa ; Tensile strength σ = 102 MPa.

Basalt-PLA skins in 0° - & 90° - direction:

Tensile stiffness E = 20 GPa ; Tensile strength σ = 330 MPa.

The outcome of the Elamx calculation is a required SR-PP thickness of 7 mm. Assuming a density of 900 kg/m³ and a product area of 1,8 m x 0,3 m, the total mass of the SR-PP stool is 3,4 kg.

Additional data and calculations for the car roofbox

The masses for the roofbox calculation in this report are the results of several assumptions. These are the assumed mechanical properties:

	Tensile Stiffness (GPa)	Tensile Strength (MPa)
PP	1,4[16]	35[17]
Carbon-Epoxy weave	70	600
Flax-PLA nonwonen[18]	13,16	90,4

[13] https://www.chemicalbook.com/ProductChemicalPropertiesCB6246352_EN.htm

[14] http://www.dflca.ch/inventories/Hintergrund/Werner_2017-report_wood_KBOB_2016.pdf

[15] https://www.woodworkdetails.com/knowledge/wood/species/imported-softwood/parana-pine/

[16] https://omnexus.specialchem.com/polymer-properties/properties/stiffness

[17] https://www.shimadzu.com/an/industries/chemicals/film/tensile-strength-of-polypropyl/

[18] D. Pantaloni, D. Shah, C. Baley and A. Bourmaud, “Monitoring of mechanical performances of flax non-woven biocomposites during a home compost degradation,” Polymer degradation and stability, vol. 177, pp. 109-166, 2020.

As example for a conventional roofbox, a roofbox out of 4 mm thick PP is assumed [19].

For the brepla flax-PLA roofbox we assume following dimensions: 126 x 44 x 30 cm. The weight of a commercial PP roofbox is 11 kg for bigger dimensions: 131 x 78 x 38 cm.[20] If we assume the roofbox shape as a beam and rescale the 11 kg to the dimensions of a brepla roofbox, the PP roofbox would have a mass of 4,7 kg. The next calculations are based on this 4,7 kg.

As a criterion to calculate the required thickness of the flax-PLA and carbon-epoxy roofbox, it is assumed that the bending stiffness and flexural strength should be higher or equal compared to the 4 mm thick PP roofbox.

To calculate the needed thickness for equal stiffness, the bending stiffness, E x I, has to be the same. With modulus E, and area moment of inertia I ($I = bh^3/12$, b = width, h = thickness). This results in a required thickness for flax-PLA of 1,9 mm and a required thickness for carbon-epoxy of 1,09 mm.

To calculate the needed thickness for equal strength, the maximum bending moment that the material can handle has to be the same (assuming 100% linear and elastic stress behaviour) in the following formula: tensile strength = maximum stress = $\sigma_{max} = - M_{max}\, y / I$, with maximum bending moment M, y = half the thickness and area moment of inertia I.

This calculation results in a required thickness for flax-PLA of 2,5 mm and a required thickness for carbon-epoxy of 0,97 mm.

The last step is to select the maximum required thickness:

Flax-PLA: 2,5 mm

Carbon-Epoxy: 1,09 mm

Knowing these thicknesses and the weight of a PP roofbox, 4,7 kg, the required material quantities can be calculated:

	density (kg/m³)	w% [21]	kg
carbon fiber	1900	55,5	1,26 kg
epoxy resin	1250*	44,5	1,01 kg
Flax fiber	1400	50	2,58 kg
PLA	1240	50	2,58 kg

* varies between 1200 and 1300 kg/m³

[19] https://www.renaultwebwinkel.nl/a-73838826/jogger/dacia-dakkoffer-480-liter/#description

[20] https://www.bol.com/be/nl/p/cam-elite-343-340-l-zwart/9200000116831123/

[21] Gopalraj, S.K.; Deviatkin, I.; Horttanainen, M.; Kärki, T. (2021) Life Cycle Assessment of a Thermal Recycling Process as an Alternative to Existing CFRP and GFRP Composite Wastes Management Options. Polymers, 13(24), 4430; https://doi.org/10.3390/polym13244430