DEVELOPMENT AND PILOT PRODUCTION OF SUSTAINABLE BIO-BINDER SYSTEMS FOR WOOD-BASED PANELS

Deliverable 5.7

Consolidated LCA, techno-economic analysis and market uptake analysis

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Lead beneficiary: CE Delft

Main contact: Martijn Broeren, Broeren@ce.nl
Other contributors Isabel Nieuwenhuijse, Ellen Schep, Geert Warringa, Geert Bergsma

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This project has received funding from the Bio Based Industries Joint Undertaking (JU) under grant agreement No 792063. The JU receives support from the European Union’s Horizon 2020 research and innovation programme and the Bio Based Industries Consortium

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1 Summary

The SUSBIND project was initiated to develop a new adhesive for particleboard (PB) and fibreboard (MDF). PB and MDF currently use urea-formaldehyde (UF) adhesives, which are derived from fossil fuels. In addition, boards made with UF emit formaldehyde during their use phase, which can be harmful to human health. The goal of the SUSBIND project was therefore to develop a bio-based, formaldehyde-free adhesive for PB and MDF, with a 5% lower carbon footprint and lower human health impact than UF adhesives.

Over the past years, the SUSBIND consortium partners have developed the 'SUSBIND adhesive'. This adhesive is partly bio-based (80% biogenic carbon[1]). It consists of biobased fructose and hydroxymethylfurfural (HMF) and fossil bis(hexamethylene)triamine (BHT). The SUSBIND adhesive has shown promising technical performance in boards produced at small scale and in a prototype final product (at Technology Readiness Level, TRL 5). Alongside the technical development of the SUSBIND adhesive, different aspects related to its environmental impact, human health effect, and market feasibility were studied.

- The **human health impact** of the SUSBIND adhesive is lower than that of UF adhesives. A first assessment based on measured emissions from boards shows that the overall human health impact of SUSBIND boards is expected to be about 40 to 55% lower than that of UF/MUF boards (based on the LCA ReCiPe 2016 human health indicator). The human health impact is mainly determined by formaldehyde emissions for both board types[2]. These are already well below the E1 emissions standard in the MUF/UF reference boards (and thus considered safe) but a further reduction of emissions in the use phase is still positive.

- The **carbon footprint** of the SUSBIND adhesive was evaluated using life cycle assessments (LCAs). The LCAs show that SUSBIND adhesive is expected to have a higher carbon footprint than UF adhesive over its entire life cycle. Depending on the amount of adhesive required and the board type (PB or MD), the carbon footprint is expected to be about equal up to about 50% higher at the current level of development of the SUSBIND adhesive (TRL 5). The carbon footprint is driven primarily by the fossil crosslinker in the adhesive, BHT. BHT contributes between 43% and 65% of the total carbon footprint of SUSBIND adhesive systems.
    - Various options to reduce the carbon footprint of the SUSBIND adhesive during further development/upscaling were evaluated. However, these options had important shortcomings, because they did not result in a sufficiently large carbon footprint reduction, are not currently commercially available, are unlikely to be technically feasible, or they could also be applied to UF adhesive systems.
    - The UF carbon footprint benchmark is relatively ambitious, as urea and formaldehyde have been produced in bulk for decades, meaning that producers have been able to optimise their processes extensively. Nevertheless, it is the most relevant benchmark for SUSBIND given its aim to reduce the carbon footprint compared to incumbent solutions.
    - An alternative fossil formaldehyde-free adhesives also exists: pMDI. The LCA shows that the SUSBIND adhesive (10% resin content) has a 5% lower carbon footprint than pMDI in PB.

- A **market uptake analysis** assessed to what extent the SUSBIND adhesive is feasible for post-project production upscaling, from a techno-economic and regulatory perspective. This analysis highlighted that the SUSBIND adhesive is technologically promising, that sufficient biomass resources are available and that more stringent formaldehyde emissions norms could support the SUSBIND

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[1] This value is calculated based on the main components (fructose, HMF and BHT). Additives are not considered.

[2] The SUSBIND adhesive does not contain formaldehyde. However, the wood chips in wood-based boards also emit smaller amounts of formaldehyde.

adhesive. However, the price, availability and carbon footprint of BHT are key uncertainties that can hinder a successful market uptake.

The SUSBIND project has successfully proven the technological feasibility of a carbohydrate-based adhesive for wood-based boards. In addition to being (partly) biobased, it can offer lower formaldehyde emissions which can be harmful to human health. At present, the carbon footprint of the SUSBIND adhesive is higher than that of UF adhesive, due to the fossil crosslinker BHT. To lower the carbon footprint of the SUSBIND adhesive, future work can focus on identifying alternatives for BHT, for instance by using bio-based or recycled feedstocks.

The remainder of this report describes the findings summarised above in greater detail. The following topics are covered:

- Chapter 2: The overall **role of the environmental and market analyses** conducted in SUSBIND, and their interaction with the other Work Packages;
- Chapter 3: The **carbon footprint results** for the SUSBIND adhesive derived using LCA, a comparison to UF adhesives and a discussion on the potential to reduce the carbon footprint in the future;
- Chapter 4: The estimated **human health impact** of SUSBIND-based boards in their use phase, compared to UF-based boards;
- Chapter 5: The **market uptake analysis**, which covers techno-economic aspects, government policies, resource availability and consumer preferences;
- Chapter 6: Final **conclusions and recommendations**.

2 Environmental and market analyses in SUSBIND

This report describes the activities and results of environmental and market analyses conducted in the SUSBIND project (within Work Package 5). These analyses were conducted in order to ensure that the produced bio-based adhesive developed has a lower carbon footprint and human health impact than the current formaldehyde-based adhesives and that the bio-based adhesive is in line with all market and regulatory requirements.

The work was split up into five tasks:

- Provide guidance in the sustainable development of a biobased binder;
- Analyse carbon footprint and human health impact of current resins;
- Develop guidelines for environmental footprint reduction at TRL 9 (including carbon footprint and human health impact analysis of the biobased binder);
- Techno-economic analysis;
- Ensure alignment with regulation and standards.

The analyses, and specifically the first two tasks, were conducted continuously throughout the project and in parallel with the technological development of new bio-based adhesives. Life cycle assessment (LCA)[3] was used to analyse the carbon footprint of existing adhesives for PB and MDF as well as new proposals by the scientific and industrial scientific partners.

By using LCA early on, we can show the environmental implications of different options so that they can explicitly be considered in the decision-making process. Environmental impacts can then be taken into account alongside other criteria, such as technical performance, feedstock availability, or costs. An example was that the project originally focused on both vegetable oil-based and carbohydrate-based adhesives. However, one of the early LCAs showed that a vegetable oil-based adhesive would be less promising from a carbon footprint point of view. Therefore, the final SUSBIND adhesive is carbohydrate-based. Nevertheless, it should be noted that the environmental performance was not the only consideration during adhesive development in SUSBIND, since proving the technical feasibility of a bio-based adhesive was a key focus.

Note that the following chapters describe the final outcomes of the environmental and market analyses, and not the intermittent results. More detailed results are available in the six other SUSBIND deliverables developed within SUSBIND Work Package 5, which contain non-confidential summaries:

- LCA current state-of-the-art resins (Deliverable 5.1);
- LCA of proposed feedstock (Deliverable 5.2);
- LCA of proposed resins (Deliverable 5.3);
- LCA of adhesive systems (Deliverable 5.4);
- Guideline for carbon footprint reduction at TRL 9 (Deliverable 5.5);
- Market uptake analysis (Deliverable 5.6).

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[3] LCA is a standardised method (ISO, 2006a) (ISO, 2006b) to determine the environmental impacts of products or services throughout their entire life cycle, i.e. from cradle to grave.

3 Carbon footprint

This chapter explains how the life cycle assessment (LCA) method was used to compare the carbon footprint of the newly developed SUSBIND adhesive to state-of-the-art UF adhesives in PB and MDF. We first describe the main/default results in Section 3.1, and then focus on carbon footprint improvement options in Section 3.2.

3.1 Carbon footprint results

3.1.1 Goal and scope

Goal and functional unit

The goal of this LCA is to compare the carbon footprint of the new SUSBIND resin and conventional, state-of-the-art UF resin when used in P2 PB and MDF. The analysis follows the ISO 14040/14044 standards for LCA (ISO, 2006a) (ISO, 2006b). The functional unit is defined as an adhesive system for 1 m^3 of board, meeting the performance requirements.

'Adhesive system' is defined in this assessment as all non-wood components in the board, i.e. the resin and any additives which contribute to meeting the technical requirements of final board products. In addition, any expected changes in the amount of wood chips or energy needed when switching from one adhesive system to the other are included. This functional unit is chosen because all properties of a board can change when using a different resin, including the amount of wood chips, the type and amount of additives, and the energy use for board pressing.

Different resin contents for the SUSBIND resin are included in the analysis, i.e. 12% and 10% resin content for P2 PB, and 12%, 10% and 8% for MDF. Because the required resin contents are not exactly known (further optimisations may be possible), it is relevant to show the effect of resin content reductions. Another resin, pMDI (polymeric methylene diphenyl diisocyanate), was added as a secondary fossil reference for PB, as it is a relevant existing alternative to formaldehyde-based resins for wood-based boards.

Environmental indicator: carbon footprint

The LCA is focused on the carbon footprint performance of the different adhesives. The carbon footprint expresses a product's or service's contribution to climate change through the emission of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). It is expressed in CO_2 equivalents (eq.). To calculate the carbon footprint, the ReCiPe 2016 (H) impact assessment method is used (Huijbregts, et al., 2016).

Biogenic carbon

This LCA deals with (partly) bio-based materials, i.e. the new SUSBIND resin and wood chips, which contain biogenic carbon (carbon recently captured from the atmosphere by plants). The flows of biogenic carbon dioxide are considered carbon neutral in this study; both their uptake from the atmosphere and emission to the atmosphere is not taken into account in the carbon footprint estimates.

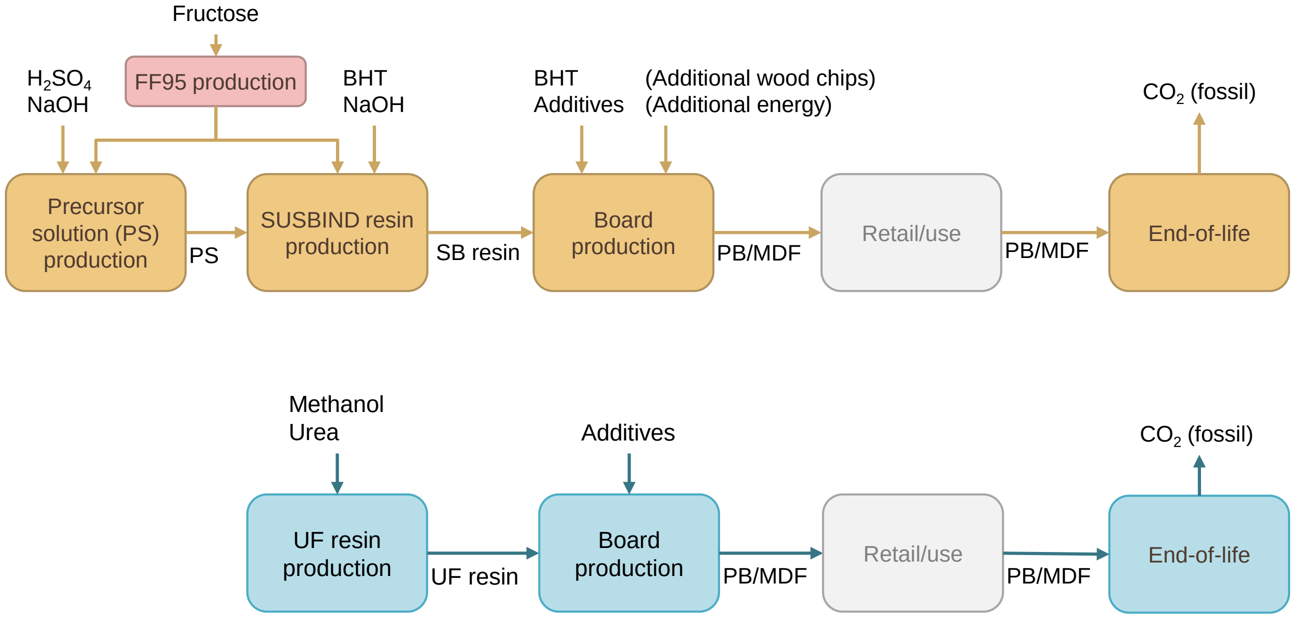
Land use change (LUC), such as the conversion of forest into agricultural land, can have a substantial carbon footprint which should be taken into account when evaluating (partly) bio-based products. Carbon emissions due to LUC are already included in the base carbon footprint analysis, as they are included in the literature source for the carbohydrate feedstock (VITO, 2022). The analysis by VITO (2022) builds upon the Agri-Footprint LCA database for bio-based (raw) materials (van Paassen, Braconi, Kuling, Durlinger, & Gual, 2019).

Scope and system boundaries

The LCA uses a cradle-to-grave scope and focuses on current production in Europe. For end-of-life, incineration without energy recovery is assumed.

Figure 1 provides an overview of the life cycle phases of the board products under study. This is a simplified scheme, as not all inputs and outputs are shown. The figure show the cradle-to-grave scope of the analysis, meaning that the whole life cycle of the boards are covered, from the sourcing of raw materials to the end-of-life (EOL).

Figure 1 - System boundaries for the analysis of the SUSBIND adhesive system (top) and the UF adhesive system reference (bottom)



Data and modelling

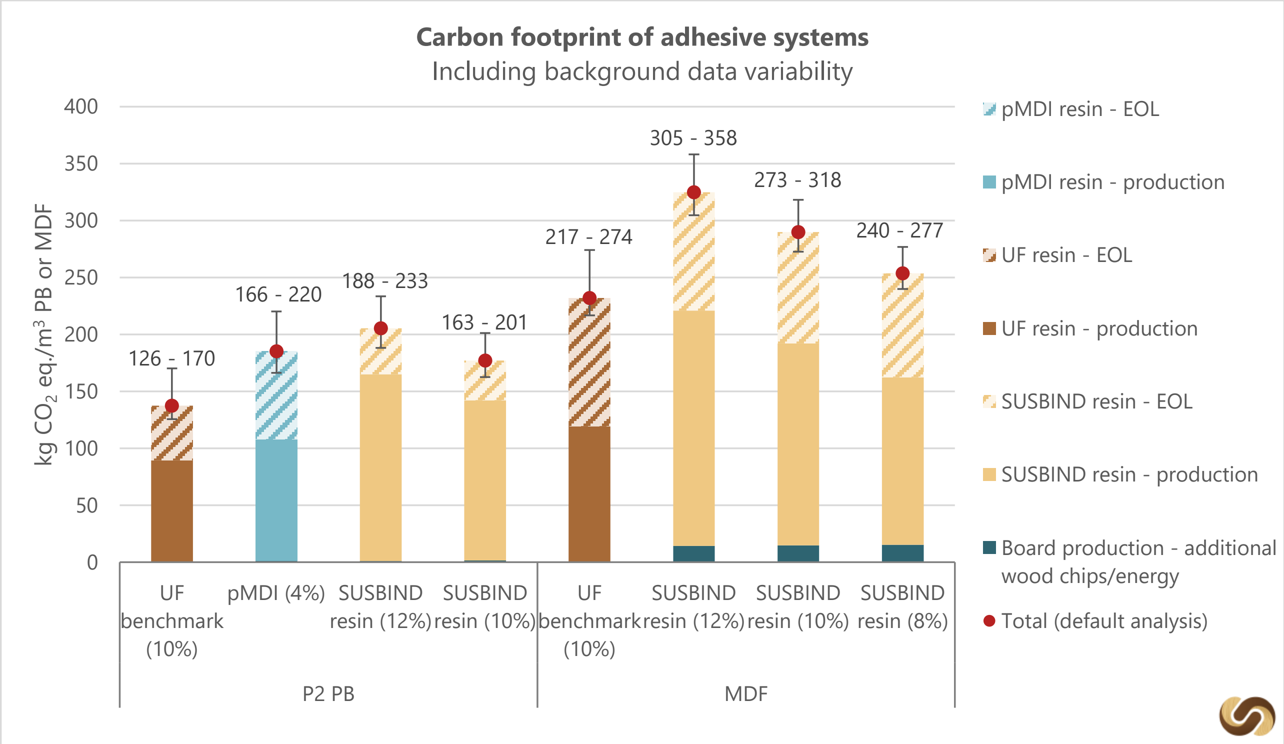
Primary process data was provided by the industrial SUSBIND project partners. This includes the preparation of UF and SUSBIND resins and the production of PB and MDF boards (i.e. wood chips, resin amounts, additives, energy). This data is supplemented with background data from literature and LCA databases including Ecoinvent (Ecoinvent, 2016) and CarbonMinds (Kätelhön, et al., 2022). The appendix of this report (Chapter 8) provides more details on the data used.

The data was used to create LCA models in the SimaPro 9.3 LCA software. Carbon footprint results were calculated using the ReCiPe 2016 Midpoint (H) method (version 1.06).

3.1.2 Carbon footprint results

The carbon footprint results are shown in Figure 2 below. In this figure, the red dots show the total (cradle-to-gate) carbon footprint of the adhesive systems. This is based on the default background data. The uncertainty bars (i.e. the black line covering the red dot) show how the results change if different background carbon footprint background data for the carbon footprints of materials are used (e.g. a value for methanol production in Germany instead of a European average for methanol production). The low value of these bars indicate how the carbon footprint would change if all the lowest carbon footprint values are used (lower value) or vice versa for the highest values.

Figure 2 - Carbon footprint of all studied adhesive systems in PB and MDF, with uncertainty range for background dataset variability



Compared to the UF benchmark for PB, the SUSBIND adhesive systems (as well as pMDI) are estimated to have a higher carbon footprint. The carbon footprint of pMDI is estimated to be 35% higher, while that of the SUSBIND resin is about 30 to 50% higher, depending on the share of resin content (10% of 12%). However, when compared to the pMDI reference, the SUSBIND adhesive system has about a 5% lower carbon footprint if a resin content of 10% can be used.

For MDF, the carbon footprint of the SUSBIND adhesive system is between 9% and 40% higher, depending on the resin content. Note that all these percentages would be smaller if the entire wood-based board, not just the adhesive system, would be considered.

The largest contributor to the carbon footprint of the SUSBIND adhesive systems is the production of the fossil crosslinker BHT. BHT production accounts for 32% to 50% of the total carbon footprints of the adhesive systems for MDF and P2 PB, respectively. During EOL, BHT is also a large contributor, since it contains fossil carbon. Its EOL contributes between 11% and 17% of the total carbon footprint.

If we consider the variability in the background data (indicated by the uncertainty bars in Figure 2), the analysis shows that all carbon footprint values could be 3-7% lower or 5-10% higher. This shows that the carbon footprint of adhesive systems based on SUSBIND resin can be comparable to the fossil benchmarks in specific instances. For example, the uncertainty range for the 10% SUSBIND resin case in PB partly overlaps with the uncertainty range for the 10% UF benchmark. The same applies for MDF in the case of 10% and 8% SUSBIND resin.

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3.1.3 Discussion and conclusions

The analysis contains some limitations that should be kept in mind when interpreting the results:

- The amount of SUSBIND resin required to produce boards with equivalent properties as UF-based boards can likely be optimised further.
- No carbon footprint is available for BHT in LCA databases. The carbon footprint of BHT is therefore determined by using hexamethylenediamine as a proxy, i.e. we are assuming that BHT production has the same carbon footprint as HMD production. Because BHT is a minor co-product created in the HMD production chain, HMD is considered a representative proxy.
- The SUSBIND boards have so far been produced at lab scale, which means that some of the values/assumptions used in this analysis may not fully translate to industrial scale production. We are for instance assuming that additive mixes will be similar and that board pressing energy is identical (P2 PB) or slightly higher in proportion to increased press times (MDF) when making SUSBIND boards compared to UF boards.
- The energy use of SUSBIND resin production is based on an estimate by CE Delft on expected production at TRL5.
- The assessment is limited to the carbon footprint (cradle-to-grave) and human health (use phase only) performance. Other environmental effects have not been studied.
- Carbon emissions due to LUC are included in the analysis, as they are taken into account in the environmental footprint of the carbohydrate feedstock based on the Agri-Footprint LCA database. An alternative LUC analysis conducted by CE Delft resulted in a higher LUC carbon footprint than the Agri-footprint estimate. This change did not affect the overall conclusions of the study.

The present analysis leads to the following conclusions regarding SUSBIND’s carbon footprint:

- The carbon footprint of the adhesive systems based on the SUSBIND resin is currently estimated at about 180 to 205 kg CO_2 eq./m^3 for P2 PB (between 12% and 10% SUSBIND resin), and 255 to 325 kg CO_2 eq./m^3 for MDF (between 12% and 8% SUSBIND resin).
- Based on these results, the SUSBIND adhesive systems are estimated to have a higher carbon footprint than the benchmark state-of-the-art UF adhesive systems. The benchmark carbon footprint values are 137 kg CO_2 eq./m^3 for P2 PB and 232 kg CO_2 eq./m^3 for MDF.
- When compared to using pMDI in PB (185 kg CO_2 eq./m^3), the SUSBIND resin has a 5% lower carbon footprint if the resin content is 10%.
- The carbon footprint of the SUSBIND adhesive systems is strongly determined by the use of fossil-based BHT, which has a high carbon footprint (during production and end-of-life).
- If variability in the available background datasets is considered, the SUSBIND adhesive system can come close to or beat the fossil benchmarks in specific instances.
- A literature comparison for UF resins showed that the carbon footprint for UF used as a benchmark here is in line with other studies. Some studies report lower carbon footprints per kg d.s. UF adhesive, but due to methodological differences (e.g. different geographical and temporal scope, production systems, background data) they may not be representative for the current state-of-the-art production in Europe.

3.2 Carbon footprint reduction options

3.2.1 Goal and approach

The default carbon footprint results show that the SUSBIND adhesive does not achieve a carbon footprint reduction compared to UF adhesives. Therefore, several carbon footprint reduction options are studied here to investigate whether and how a carbon footprint reduction could be realised. The analysis covers effects of upscaling, ingredient sourcing, resin formulation and board formulation. It focuses especially on BHT because of its large contribution to the carbon footprint. The analysis discusses six carbon footprint improvement options in detail and covers other developments relevant to the carbon footprint.

The aim is to assess whether such improvements can substantially reduce the carbon footprint of using a SUSBIND adhesive system in wood-based boards. The cradle-to-grave carbon footprint of the SUSBIND adhesive system should be reduced by 9% (MDF, 8% resin) or by 22% (P2 PB, 10% resin) to have the same carbon footprint as UF adhesive systems. However, as SUSBIND's formulated goal for TRL5 is to offer a 5% carbon footprint reduction compared to UF adhesive systems, this means that larger reductions are required.

Some key remarks on this assessment are in order:

- The UF carbon footprint benchmark is relatively ambitious, as it is based on state-of-the-art production in Europe. In addition, urea and formaldehyde are relatively simple chemicals that have been produced in bulk for decades, meaning that producers have been able to optimise their processes extensively. Nevertheless, it is the most relevant benchmark for SUSBIND given its aim to reduce the carbon footprint compared to incumbent solutions.
- Due to uncertainties related to the early stage of development, the assessment of the six improvement options is partly based on assumptions and sometimes uses a break-even approach (i.e. 'What is required to meet the carbon footprint target?'). For example, since a bio-based production route to BHT is hypothetical at this point, we do not know whether its cradle-to-gate carbon footprint would be comparable to fossil BHT. When interpreting the results, these limitations should be kept in mind.

3.2.2 Carbon footprint reduction options

The assessment of the six carbon footprint reduction options is summarised in Table 1 below. This shows that all options can result in carbon footprint reductions and are thus relevant directions for further research. However, they all have different shortcomings as well, since they:

- do not result in a sufficiently large carbon footprint reduction (alternative fossil crosslinkers, reducing energy consumption of SUSBIND resin production);
- have not yet been developed/are not commercially available (bio-based BHT);
- are unlikely to be technically feasible (substantially lower amount of BHT, substantially lower amount of resin); and/or
- can also be applied to UF adhesive systems (bio-based wax emulsion, lower amount of resin).

Table 1 – Results for various carbon footprint reduction options for SUSBIND resin

Improvement option	Most important assumption(s)	Effect on overall carbon footprint
Reduce amount of BHT	Rest of board formulation/production stays the same	P2 PB (10% resin): if BHT reduction of 35% can be achieved, carbon footprint is equal to UF-based P2 PB MDF (8% resin): if BHT reduction of 20% can be achieved, carbon footprint is equal to UF-based MDF

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Improvement option	**Most important assumption(s)**	**Effect on overall carbon footprint**
	Technical requirements can still be met with reduced BHT content	
Switch to alternative crosslinker	Rest of resin formulation stays the same	P2 PB (10% resin): if alternative crosslinker has a cradle-to-grave carbon footprint of max. 5.2 kg CO_2 eq./kg, carbon footprint is equal to UF-based P2 PB MDF (8% resin): if alternative crosslinker has a cradle-to-grave carbon footprint of max. 6.4 kg CO_2 eq./kg, carbon footprint is equal to UF-based MDF
Change BHT production: bio-based	Rest of resin formulation stays the same Impact of production of bio-based BHT is the same as of fossil BHT No EOL emissions for bio-based BHT	P2 PB (10% resin): if bio-based BHT with set assumptions can be used, overall carbon footprint is still higher than UF-based P2 PB MDF (8% resin): if bio-based BHT with set assumptions can be used, overall carbon footprint is lower than UF-based MDF
Reduce energy consumption of resin production	-	Even if the impact of energy use would be reduced to 0, the total carbon footprints of the SUSBIND adhesive systems would still be higher than that of UF adhesive systems
Change additives: bio-based hydrophobic wax	Rest of board formulation stays the same Impact of production of bio-based wax is the same as of fossil wax No EOL emissions for bio-based wax	P2 PB (10% resin): the overall carbon footprint can be reduced by 3% using bio-based wax with set assumptions. However, as the same amount of wax is used in UF-based PB, the effect on the carbon footprint would be bigger and as such the difference between the two would increase. MDF (8% resin): the overall carbon footprint can be reduced by 25% using bio-based wax with set assumptions. However, as the same amount of wax is used in UF-based MDF, the effect on the carbon footprint would be bigger and as such the difference between the two would increase.
Reduce amount of resin used	Technical requirements can still be met with reduced resin content	P2 PB (10% resin): the break-even point to achieve the same carbon footprint as UF-based P2 PB is a resin content of 7%. It is unknown whether a lower resin content can be used for UF-based P2 PB as well. MDF (8% resin): the break-even point to achieve the same carbon footprint as UF-based MDF is a resin content of slightly below 7%. It is unknown whether a lower resin content can be used for UF-based MDF as well.

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4 Human health

4.1 Goal

When wood-based boards are used in furniture applications, various substances can be released from the wood chips and adhesive used, some of which can be toxic. Since SUSBIND aims to create boards which reduce emissions that are toxic to humans, here we evaluate[4] to what extent the emissions from SUSBIND boards are toxic and whether they can have a higher impact on human health than the incumbent solutions. Note that the analysis in this section is based on the first prototypes of boards made using the SUSBIND resin and therefore gives a first indication.

In March 2022, SUSBIND partner IKEA conducted standardised emissions tests of volatile organic chemicals (VOCs) and formaldehyde for three pieces of particleboard: a ‘SUSBIND board’ produced by Egger and two industrially produced standard reference boards. The latter use UF in its core layers and melamine-urea-formaldehyde (MUF) in its surface layers. The tests, conducted based on the ISO 16000-3 standard, report the concentration of specific substances at a specified time after sample introduction.

IKEA’s testing showed that all boards performed very well with regard to their formaldehyde emissions. The reference boards, which use formaldehyde-based resins, showed formaldehyde emission levels which were well below the levels required for the E1-standard. This means the formaldehyde emissions are already lower than required by European Union legislation.

As expected, IKEA’s testing shows that the boards emit different substances and in different amounts. For example, the reference board has higher formaldehyde emissions, while the SUSBIND board has higher acetic acid emissions. It is therefore relevant to consider how these different emissions compare in order to investigate whether the SUSBIND board does not represent a ‘step backwards’ from a human health perspective.

4.2 Approach and data

To obtain a first indication of the potential human health impact of boards during the use phase, the measured concentrations of different substances were used to calculate an LCA-based indicator. The indicator used is the human health score from the ReCiPe 2016 (Endpoint (H) V1.06 / World (2010) H/A) method, expressed in disability-adjusted life years (DALY). The method uses the underlying USETOX toxicity model, containing toxicological information on 3094 substances.

This score aggregates different (midpoint) indicators such as human carcinogenic/non-carcinogenic toxicity, ozone formation and fine particulate matter formation. This enables us to compare the overall human health impact of the different emissions based on current state-of-the-art knowledge.

Some important limitations of this analysis should be kept in mind when interpreting the results:

- The comparison is based on tested concentrations after 48 hours according to the ISO 16000-3 standard. While this is helpful to check how damaging different substances are expected to be, the concentrations are likely not representative of the full emissions occurring during the full use phase of a piece of furniture made from wood-based boards.
- Because we are only estimating emissions occurring during the use phase, the results are not representative of potential human health impacts occurring during e.g. the sourcing of materials, production of final products, or final end-of-life of the boards.

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[4] The full version of this assessment is included in SUSBIND Deliverable 5.4.

- The emissions are derived from two specific pieces of board, using either SUSBIND resin or a mix of MUF and UF resins. The emissions may be influenced by the type and sourcing of wood chips, resin composition, additives used, board production process, etc. Some variability in the emissions is therefore to be expected between boards with the same composition, and there may be opportunities to reduce specific substance emissions. It should further be noted that the tested SUSBIND board was produced at laboratory scale.
- Tests were conducted using particleboards. Emissions from MDF could differ from the values used here.
- CE Delft cannot comment on the accuracy of the applied testing method, nor is it known to us whether all substances emitted from boards can be detected in this test.
- Human health impacts are more complex to model than for instance climate change impacts. While the impact of emissions of greenhouse gases do not depend on where the emissions take place, this is not the case for e.g. toxicity assessments, where damage depends on where a substance is emitted (e.g. near populations or not), where it ends up (e.g. inside an organism or not), how it interacts with other substances, background concentrations, etc. The ReCiPe 2016 method applied here therefore represents the current level of LCA-based human health impact estimates.

4.3 Results and interpretation

Figure 3 shows the estimated human health score of the reference board and the SUSBIND board (lower is better). These are the measured emissions[5] multiplied by characterisation factors from the ReCiPe 2016 method indicating how damaging an emission is. The figure shows which substances contribute to the overall human health impact score. Emissions which do not have any human health impact effect according to the ReCiPe 2016 method are not shown (e.g. butyric acid). Overall, this first assessment shows that the overall human health impact of SUSBIND boards is expected to be about 40 to 55% lower than that of UF/MUF boards.

For both boards, emissions of formaldehyde are the largest contributor to the human health score. However, the formaldehyde emissions of the reference board are already far below the E1 formaldehyde emission standard and thus considered safe. This assessment therefore highlights that the new and/or higher emissions from the SUSBIND boards are not expected to have a major toxic impact, when accounting for the specific substances and their amounts. Although this analysis contains important uncertainties, based on the results it is considered unlikely that the wood-based boards using SUSBIND resin lead to increases in emissions that are harmful to human health, particularly due to the lower formaldehyde emissions.

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[5] Note that it was also checked whether BHT or HMD emissions are considered toxic in the ReCiPe 2016 method (i.e. whether they have characterisation factors). This was not found to be the case, meaning they are considered not harmful or have not been sufficiently studied. However, since these substances were not detected in IKEA's tests, there is no reason to assume that any emissions of BHT or HMD occur.

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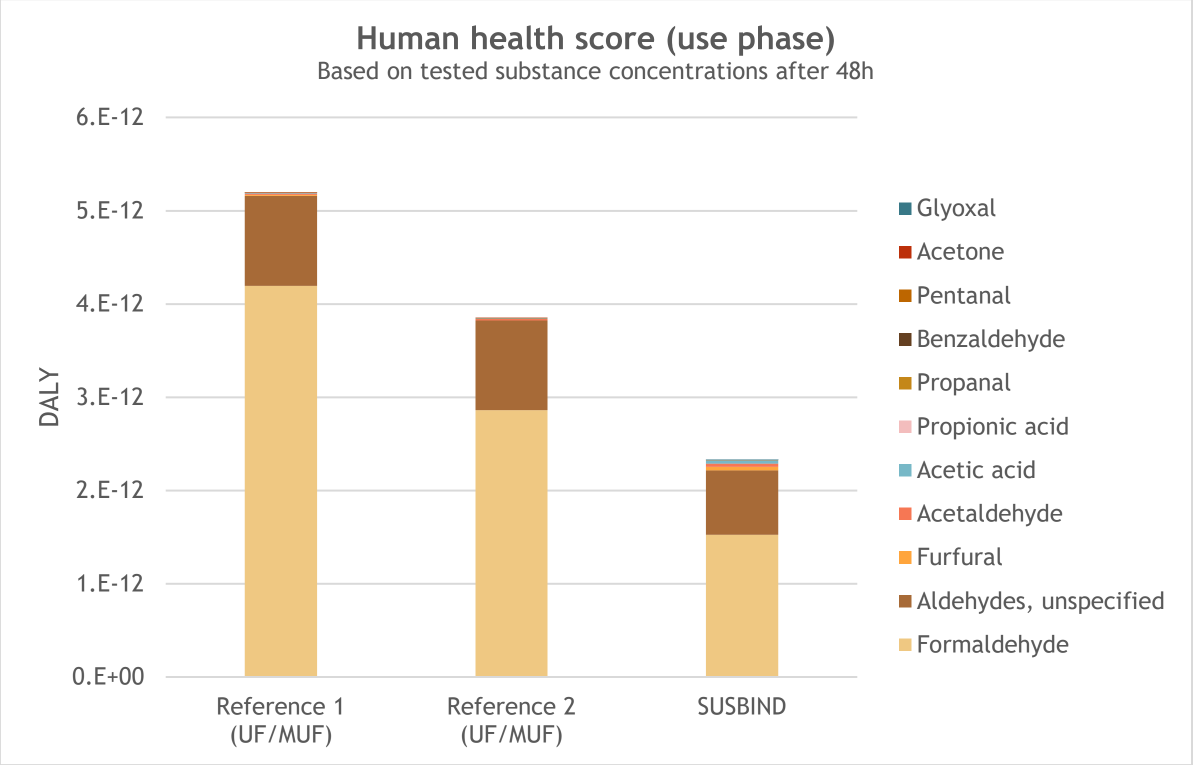
Figure 3 - Human health score of use phase emissions for UF/MUF reference boards and SUSBIND boards



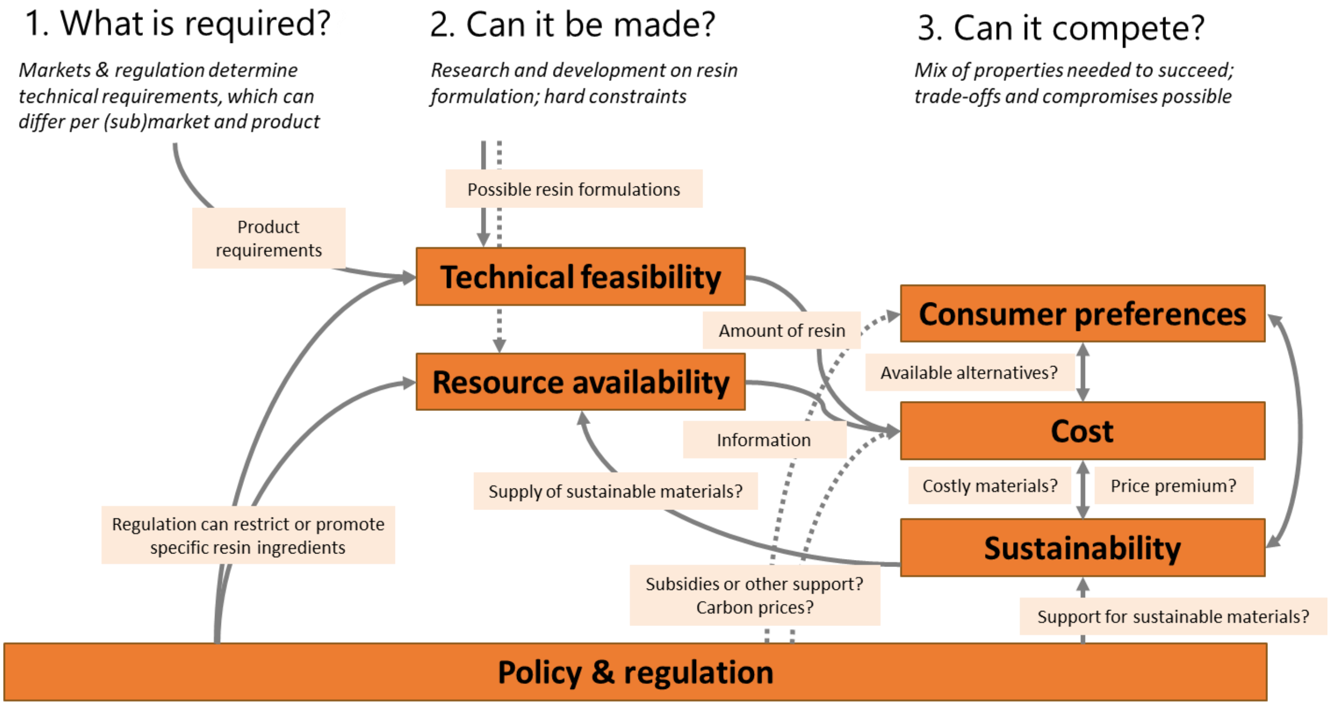
5 Market uptake analysis

In this market uptake analysis[6] we assess to what extent the SUSBIND resin can compete with current state-of-the art resins and is feasible for post-project production upscaling, from a techno-economic and regulatory perspective.

5.1 Analytical framework

To gain more insights into the opportunities for a successful market uptake of SUSBIND resin an analytical framework has been developed. This is illustrated in Figure 4.

Figure 4 – Analytical framework for investigating the potential market uptake, including (indicative) relations between success factors



The analytical framework is centred around three subsequent questions: 1) What is required? 2) Can it be made? and 3) Can it compete? The first question determines the requirements for the products, in this case a formaldehyde-free bio-based resin for wood-based panels. This market uptake analysis does not focus specifically on the first question, but it is crucial for determining technical feasibility of a new resin (as was done in SUSBIND Work Packages 2, 3 and 4). The technical requirements are driven by market demands and can differ per (sub)sector. In addition, regulation can play a role here.

The second question (can it be made?) is crucial for market uptake and determines whether market introduction of the proposed resin is possible. In this stage, research and development are conducted to develop a resin formulation that can meet the technical requirements. **Technical feasibility** and **resource availability** are two key criteria here.

The third question (can it compete?) further determines whether market introduction is successful. Once it is clear that a resin offers sufficient technical performance and can be produced at scale, other 'softer' criteria

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[6] The full version of this assessment is included in SUSBIND Deliverable 5.6.

This project has received funding from the Bio Based Industries Joint Undertaking (JU) under grant agreement No 792063. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio Based Industries Consortium.

determine whether a resin is successful. Here, we structure the discussion around the **business case**, **consumer preferences** and **sustainability**. Between these criteria, trade-offs and compromises are possible. These criteria can be influenced by **policy and regulation**.

5.2 Market uptake analysis for the SUSBIND adhesive

For the SUSBIND resin we analysed the criteria that should be met for a successful market uptake. From the first lab and product prototype tests we expect that technical feasibility is sufficient and that there seem no big problems that negatively affect the upscaling potential.

While fructose from maize/wheat is sufficiently available, for BHT the availability of resources and production capacity is unsure at the moment, also caused by scarcity in all resource markets. BHT is currently only produced as a by-product, so there is no dedicated production. According to producers, sufficient raw materials are available and production capacity can be created if demand is high enough, although it has to be researched if and how dedicated production can take place. Assuming that new BHT production capacity would need to be built and that this could take several years at least, it would not be possible to scale up the use of SUSBIND resin in the shorter term.

On the environmental aspects, an initial assessment concluded that the SUSBIND adhesive is estimated to have a lower[7] human health impact during the use phase than reference UF/MUF boards (which are already well below the legal emission limits), due to their lower formaldehyde emissions. The carbon footprint results show that SUSBIND adhesive systems can come close to the footprint of UF in best case conditions, but that a major carbon footprint reduction is not likely.

The business case for the SUSBIND resin is unsure, particularly because of uncertainty about the bulk BHT price. Assessing the current business case for SUSBIND resin production is complicated by current historically high and volatile resource prices. It is likely that the price of the SUSBIND resin will be higher than the current UF price (which is low due to the optimized production process). Our analysis shows that the maximum price of BHT at which SUSBIND resin is cost-competitive is a factor 5 lower than the current market prices. In case consumers are willing to pay 30% more for a wood-based panel using the SUSBIND resin, the resin would be competitive with UF and resin costs will be 30-50% of total production costs. Regulation can influence product prices if subsidies or other financial incentives are used. On the other hand, prices of the incumbent boards using UF can increase if regulation leads to restrictive production requirements, like the formaldehyde release emission standards for panels containing UF.

Currently, there is no restricting regulation for the SUSBIND resin, but there is a risk for more stringent regulation with respect to the use of fossil ingredients and food crops for material applications.

Finally, furniture / wood based panel producers decide whether to use the SUSBIND resin whilst consumers decide whether to buy the product. In some market segments, consumers are willing to pay a price premium for a more healthy or sustainable product, but in the bulk market price is important. A market survey conducted within the SUSBIND project shows that more than half of the European consumers is willing to pay a price premium of – on average – around 15% per furniture product. For consumers, price and comfort are the most important determinants in a buying decision. Health and sustainability characteristics are less important.

Table 2 below summarizes the perspective towards market uptake in a compliance checklist:

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[7] A first assessment based on measured emissions from boards shows that the overall human health impact of SUSBIND boards is expected to be about 40 to 55% lower than that of UF/MUF boards (based on the ReCiPe 2016 human health indicator).

Table 2 – Compliance checklist for successful market uptake of novel resins for wood-based panels, applied to SUSBIND adhesive compared to urea-formaldehyde (UF) adhesive

Criterion	**Findings**	**Conclusion**
Technical feasibility	• SUSBIND adhesive production proven on a laboratory scale and prototype product • Sufficient technical properties • No insuperable issues	√
Availability of resources and production capacity	• Availability of BHT is uncertain, likely insufficient for large-scale implementation of SUSBIND adhesive • Sufficient availability of bio-based materials • Dedicated production capacity BHT can be created, but this is a longer-term option that should be further investigated	?
Business case	• Current price of BHT is uncertain and volatile, but price may decrease if production is scaled up • Price of UF is relatively low due to optimized production process; however, higher formaldehyde emission standards could increase price • Business case assessment is complicated by current historically high and volatile resource prices • Without additional willingness to pay by consumers, SUSBIND adhesive is unlikely to be cost-competitive	?
Sustainability: carbon footprint and human health effects	• Over 50% lower formaldehyde emissions than incumbent UF/MUF boards; other emissions are higher (acetic acid, furfural) but overall reduced human health impact in furniture use phase • Carbon footprint of SUSBIND adhesive system is about 10 – 30% higher than UF adhesive system in default LCA analysis, due to use of fossil BHT • Carbon footprint of SUSBIND can come close to UF in specific cases, but no substantial reduction expected	?
Regulation, certification and standards	• Regulation and standards (public and private) are becoming increasingly stringent for formaldehyde emissions during the use phase of furniture. • No restricting (or supporting) regulation for the SUSBIND adhesive at the moment • Risk of more stringent regulations with regard to fossil ingredients and use of food crops for material applications • Opportunity for SUSBIND if formaldehyde regulation becomes more stringent	√
Consumer preferences	• In some market segment, consumers are willing to pay a premium for a formaldehyde-free or lower carbon footprint product, but in bulk market price is important • In a SUSBIND survey, consumers indicated they are willing to pay on average 15% more for a formaldehyde-free furniture product	√

	• Sustainability and health are important for consumers, but price and comfort are more important • Opportunity for SUSBIND is that acceptance among the general public for formaldehyde-containing products can decrease	

5.3 Market uptake analysis conclusion and recommendations

We conclude that the SUSBIND project has resulted in the development of an adhesive that meets technical requirements, but as shown in the checklist (Table 2), the price, availability and carbon footprint of BHT are the main uncertainties that can hinder a successful market uptake. As indicated in the checklist (by using a '?' instead of an 'x'), these issues can potentially be overcome, especially in the longer term. The business case for SUSBIND adhesive can shift over time, partly depending on government policies, and it may be possible to develop and install new production capacity for BHT with a lower carbon footprint.

It is recommended to further investigate the options for upscaling and the find out the corresponding price effect. Since BHT is the main barrier for market uptake, in parallel it is relevant to continue investigating alternative crosslinkers to replace BHT or to develop alternative production routes for BHT which can address the production capacity, environmental footprint and cost concerns.

6 Conclusions and recommendations

The SUSBIND project was initiated to develop a new adhesive for particleboard (PB) and fibreboard (MDF). The reason behind this was twofold:

- PB and MDF currently use urea-formaldehyde (UF) adhesives, which are derived from fossil fuels.
- Boards made with UF emit formaldehyde during their use phase, which can be harmful to human health.

The goal of the SUSBIND project was therefore to develop a bio-based, formaldehyde free adhesive for PB and MDF, with a 5% lower carbon footprint and lower human health impact than UF adhesives.

Over the past years, the SUSBIND consortium partners have developed the 'SUSBIND adhesive'. This adhesive is partly bio-based (80% biogenic carbon[8]). It consists of biobased fructose and hydroxymethylfurfural (HMF) and fossil bis(hexamethylene)triamine (BHT). Within the project, environmental and market analyses were conducted in order to verify the potential human health benefits, to compare the carbon footprint of the new adhesive and to provide advice on carbon footprint reduction options, and to assess its potential for large-scale introduction from a techno-economic and market point of view.

The key conclusions of these environmental and market assessments are as follows:

- The **human health impact** of the SUSBIND adhesive is lower than that of UF adhesives. A first assessment based on measured emissions from boards shows that the overall human health impact of SUSBIND boards is expected to be about 40 to 55% lower than that of UF/MUF boards (based on the ReCiPe 2016 human health indicator). The human health impact is mainly determined by formaldehyde emissions. These are already well below the E1 emissions standard in the MUF/UF reference boards (and thus considered safe).

- The **carbon footprint** of the SUSBIND adhesive was evaluated using life cycle assessments (LCAs). The LCAs show that SUSBIND adhesive is expected to have a higher carbon footprint than UF adhesive over its entire life cycle. Depending on the amount of adhesive required and the board type (PB or MD), the carbon footprint is expected to be about equal up to about 50% higher at the current level of development of the SUSBIND adhesive. The carbon footprint is driven primarily by the fossil crosslinker in the adhesive, BHT. BHT contributes between 43% and 65% of the total carbon footprint of SUSBIND adhesive systems.

- The **market uptake analysis** assessed to what extent the SUSBIND adhesive is feasible for post-project production upscaling, from a techno-economic and regulatory perspective. This analysis highlighted that the SUSBIND adhesive is technologically promising, that sufficient biomass resources are available and that more stringent formaldehyde emissions norms could support the SUSBIND adhesive. However, the price, availability and carbon footprint of BHT are key uncertainties that can hinder a successful market uptake.

The carbon footprint performance, as well as the high price and limited availability of BHT, are thus the key barriers identified for the SUSBIND adhesive. For the carbon footprint, it can be noted that the UF carbon footprint benchmark is relatively ambitious, as urea and formaldehyde have been produced in bulk for decades, meaning that producers have been able to optimise their processes extensively. Nevertheless, it is the most relevant benchmark for SUSBIND given its aim to reduce the carbon footprint compared to incumbent solutions.

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[8] This value is calculated based on the main components (fructose, HMF and BHT). Additives are not considered.

Various options to reduce the carbon footprint of SUSBIND adhesive have been evaluated. However, these options had important shortcomings, because they did not result in a sufficiently large carbon footprint reduction, are not currently commercially available, are unlikely to be technically feasible, or they could also be applied to UF adhesive systems.

Nevertheless, it is possible that a combination of options would enable the SUSBIND adhesive to achieve its goal of a 5% carbon footprint reduction compared to UF resin[9]. However, the carbon footprint of UF adhesives can also be reduced by improving its key production steps (ammonia production and methanol production). Overall, we consider it unlikely that a truly substantial (e.g. >50% compared to UF) carbon footprint reduction would be achieved when the SUSBIND adhesive system is based around fossil BHT, or other fossil amine crosslinkers.

In conclusion, the SUSBIND project has successfully shown that a carbohydrate-based adhesive for wood-based boards is technologically feasible. Moving forward, a promising direction is to consider whether alternatives for the fossil crosslinker BHT would be able to offer a lower carbon footprint, e.g. when based on bio-based or recycled feedstocks. If, from a technical performance point of view, it is required to use amine groups in the crosslinker, the source of the nitrogen used should be considered as well.

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[9] In addition, it can be noted that larger carbon footprint reductions are required in order to meet the European climate change goals (e.g. 55% emission reduction by 2030).

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8 Appendix: LCA inventory

In the life cycle inventory phase, an inventory is made of all the elementary flows from and to nature within the system boundaries that are associated with feedstock production. This appendix describes the data used to model the foreground and background systems of the study. We first discuss the foreground data, moving through the different life cycle stages in Section 8.1 (production of the UF and pMDI benchmarks), Section 8.2 (production of SUSBIND resin), Section 8.3 (board production), and Section 8.4 (end-of-life). Then, we provide an overview of background datasets used in Section 8.5.

This chapter provides an overview of non-confidential parts of the inventory, such as assumptions and data from public literature. Confidential data has been removed.

8.1 Production of UF resin and pMDI benchmarks

UF was selected as the state-of-the-art benchmark used to compare the newly developed SUSBIND resin with. It is widely used in both P2 PB and MDF board production and its production is well-optimised. SUSBIND project partner Egger has provided the data used for the carbon footprint analysis. This data is confidential.

pMDI resin can be used as an alternative to UF resin in P2 PB. MDI from the LCA database CarbonMinds was used as a proxy for the environmental impact of pMDI.

8.2 Production of SUSBIND resin

The SUSBIND resin (i.e. Fructose-HMF-BHT resin) is a water-based resin with a dry solid content of 57.4% (Egger information), produced in two steps:

1. Precursor solution production;
2. Resin synthesis.

8.2.1 Production of precursor solution

In the precursor solution production step, fructose (FF95) is converted to HMF. Table 3 provides the overall materials balance for precursor solution production, as included in the environmental model. The data was provided by WoodK+ and Egger.

The environmental impact also depends on the energy use of the process. Based on calorific measurement results provided by Egger, CE Delft derived a rough first estimate of the heat and electricity requirements of the process at pilot scale/TRL 5. This estimate accounts for heating the materials, cooling the materials, heat losses when maintaining a specific temperature over time, and stirring. The energy requirement of producing/maintaining a vacuum is not taken into account due to missing information. To calculate the volume of the reactor, a batch production of 100 kg was assumed. These first estimates are uncertain due to the production scale on which the estimates are based.

Table 3 - Inventory (materials only) of 680 gram precursor solution production

Material	Quantity	Unit	Comments

Inputs			
Fructose solution	595.7	g	FF95 fructose sirup. Contains 70.5% solids. Assumed all solids are fructose.
Sulfuric acid catalyst (96%w/w solution)	2.9	g	
Sodium hydroxide (for neutralisation)	8.5	g	Concentration: 30%.
Deionized water	101.3	ml	To dilute acid catalyst
Sodium dithionite	7	g	
Electricity	0.357	kWh	Electricity is supplied using the average (European) grid mix
Heat	2.88	kJ	Heat is assumed to be supplied using natural gas
Outputs			
Precursor solution	680	g	Composition: 60 g/l HMF, 210 g/l fructose, 1.5 g/l formic acid, 5.4 g/l levulinic acid, some humin side products.

8.2.2 Fructose-HMF-BHT resin synthesis

During the resin synthesis step, the concentrated precursor solution is reacted with additional fructose (FF100) and BHT to create a resin. Table 4 provides the overall material balance for resin synthesis as used in the current analysis (provided by WoodK+).

CE Delft derived a rough first estimate of the heat and electricity requirements of the process at pilot scale/TRL 5 based on Based on a calorific measurement results provided by Egger. The approach is equivalent to precursor solution production. These first estimates are uncertain.

Table 4 - Inventory (materials only) of 1500 g Fructose-HMF-BHT resin synthesis

Material	Quantity	Unit	Comments
Inputs			
Precursor solution	643.4	g	From previous step; see Section 8.2.1
Fructose solution	744.3	g	FF95 fructose sirup. Contains 70.5% solids. Assumed all solids are fructose.
Bishexamethylenetriamine	141.7	g	
Sodium hydroxide (for neutralisation)	6	g	Range: 5 to 6 g. Neutralization of FF95 syrup, small amounts
Electricity	0.016	kWh	Electricity is supplied using the average (European) grid mix
Heat	666	kJ	Heat is assumed to be supplied using natural gas
Outputs			
Fructose-HMF-BHT resin	1500	g	57.4% d.s. content. Fructose-HMF-BHT ratio 3.7:0.2:1

8.3 Board production

Table 5 provides the inputs and outputs for P2 PB production. CE Delft have based these on internal data from and discussions with Egger in May 2022.

All values are provided for 1 m^3 P2 PB at 650 kg / m^3. The comparison is based on boards meeting IKEA specifications. However, some remarks are in order here:

- The UF data represents industrial production of 18 mm boards meeting IKEA specifications.

- pMDI-based boards are not a standard product for Egger. The data here is based on lab-based production.
- SUSBIND boards are based on lab boards (max. 16 mm thickness). At 12% adhesive content, the SUSBIND boards can meet IKEA specifications. At 10%, this does not seem to be the case, although further optimisations are possible.
- The resin content for SUSBIND boards is calculated based on both the Fructose-HMF-BHT resin ánd the separately added BHT.

Table 5 - Inventory for board production for 1m^3 P2 PB in SUSBIND analysis. All values for 650 kg/m^3 board.

Material	**Quantity**				**Unit**	**Comments**
	10% UF	**4% pMDI**	**12% SUSBIND**	**10% SUSBIND**		
Inputs – materials (d.s. content)						
Wood chips (additional amount)	514.8	541.0 (+26)	534.6 (+20)	548.3 (+33)	kg (d.s)	See footnote [10]
UF-based resin (65%)	51.5				kg (d.s.)	
pMDI (100%)	1.0	26.0			kg (d.s.)	
Fructose-HMF-BHT resin (57.4%)			55.5	47.5	kg (d.s.)	
BHT (100%)			8.6	7.4	kg (d.s.)	
Ammonium nitrate (60%)	1.5				kg (d.s.)	
Wax emulsion (47%)	2.0	2.0	2.0	2.0	kg (d.s.)	
Urea	1.2				kg (d.s.)	
Release agent		0.9			kg (d.s.)	
Demiwater additional	40.0	70.5	0.0	0.0	kg	
Inputs – energy						
Electricity (additional amount)	91	91 (0)	91 (0)	91 (0)	kWh	
Heat (additional amount)	299.8	299.8 (0)	299.8 (0)	299.8 (0)	kWh	
Outputs						
PB – 10% UF	1				m^3	650 kg/m^3
PB – 4% pMDI		1			m^3	650 kg/m^3
PB – 12% SUSBIND			1		m^3	650 kg/m^3
PB – 10% SUSBIND				1	m^3	650 kg/m^3

Table 6 provides the current LCA models for MDF production. CE Delft have based these on internal data from and discussions with Valbopan in May 2022.

All values are provided for 1 m^3 MDF at 750 kg / m^3 (UF boards) or 730 kg / m3 (SUSBIND boards) and are based on board of 18 mm thickness. The comparison is based on boards meeting standard MDF specifications. Some remarks are in order here:

- Over the past period, Valbopan has tested SUSBIND boards with different adhesive amounts: 12%, 10% and 8%. The most recent testing results suggest that at 8% adhesive content, SUSBIND boards can meet standard MDF specifications.

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[10] Note that the amount of wood added to boards using SUSBIND resin is higher when compared to boards using UF, even when both boards use 10% resin and target the same board density. Egger has indicated that this is due moisture requirements for board production. In UF-based boards, additional moisture needs to be added to the wood chips, resin and additives. In the case of board using SUSBIND resin, the resin itself already contains sufficient moisture, which in turn means that more wood chips are added to achieve the desired board density.

- The adhesive content for SUSBIND boards is calculated based on both the Fructose-HMF-BHT resin and the separately added BHT.

Table 6 - Inventory for board production for 1m^3 MDF in SUSBIND analysis. All values for 730 kg/m^3 board, except for 10% UF which is 750 kg/m^3.

Material	Quantity				Unit	Comments
	10% UF	12% SUSBIND	10% SUSBIND	8% SUSBIND		
Inputs – materials (d.s. content)						
Wood chips (additional amount)	662.3	633.7 (-26)	645.2 (-14)	657.2 (-2)	kg (d.s)	
UF-based resin (65%)	66.23				kg (d.s.)	
Fructose-HMF-BHT resin (57.4%)		65.8	55.9	45.5	kg (d.s.)	
BHT (100%)		10.2	8.7	7.1	kg (d.s.)	
Ammonium sulfate (60%)	1.2				kg (d.s.)	
Wax emulsion (47%)	20.3	20.3	20.3	20.3	kg (d.s.)	
Inputs - energy						
Electricity (additional amount)	500	540 (+40)	540 (+40)	540 (+40)	kWh	Increase proportional to increased press times for SUSBIND
Diesel (additional amount)	1.64	1.64 (0)	1.64 (0)	1.64 (0)	litre	For forklifts etc.
Outputs						
MDF – 10% UF	1				m^3	750 kg/m^3
MDF – 12% SUSBIND		1			m^3	730 kg/m^3
MDF – 10% SUSBIND			1		m^3	730 kg/m^3
MDF – 8% SUSBIND				1	m^3	730 kg/m^3

8.4 End-of-life

For end-of-life (EOL), the default analysis assumes the boards are incinerated (full oxidation) without energy recovery. During incineration, all carbon present in the adhesive system is converted into CO_2 emissions. Fossil carbon present in the adhesive system contributes to the overall carbon footprint. Emissions of biogenic carbon are not taken into account in the carbon footprint, since this carbon was removed from the atmosphere during feedstock cultivation.

The SUSBIND resin is partly bio-based (fructose inputs) and partly fossil (BHT). Based on its production processes (see Sections 8.2.1, 8.2.2), the carbon in the resin is estimated to be about 80% bio-based.

To calculate the EOL CO_2 emissions of P2 PB or MDF, the following formula[11] can be applied:

$$\text{EOL CO}_2\text{ emission} = \sum_{x} \text{Amount}_x * \text{ Molecular weight}_x * \text{ Share fossil carbon}_x * 44/12$$

Where:

EOL CO_2 emission = end-of-life fossil CO_2 emissions of adhesive system, in kg CO_2 / m^3;

Amount$_x$ = amount of input material x required in production of adhesive system, in kg d.s. / m^3;

Molecular weight$_x$ = molecular weight of input material x, in g / mol;

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[11] It can be noted that this formula assumes that all (carbon-containing) material inputs are converted into CO_2 eventually. This is appropriate for the products studied here, since the production processes do not create any co-products.

Share fossil carbon$_x$ = share of carbon in molecular weight of input material x, dimensionless;

44/12 = conversion factor from carbon (12 g / mol) into carbon dioxide (44 g / mol).

8.5 Selected background datasets

For the background system, Table 7 lists which datasets were used in the SimaPro model. Unless mentioned otherwise, datasets were taken from the Ecoinvent v3.6 LCA database (system model: Cut-off by classification) or the CarbonMinds LCA database. Where necessary, specific assumptions are listed as well.

For chemicals that are supplied in a solution (e.g. ammonium nitrate or sodium hydroxide), the main ingredient is mentioned in Table 7. The remainder of the solutions is assumed to be deionised water (see entry 'Water in solutions').

Table 7 - Datasets used in SimaPro modelling and related assumptions

Material/energy	Dataset used in model	Assumptions/comments
Fructose	Life Cycle Assessment study of starch products for the European starch industry association (Starch Europe): sector study (VITO, 2022)	
Sulfuric acid	Sulfuric acid {RER}| market for sulfuric acid | Cut-off, U	Ecoinvent LCA database
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	Ecoinvent LCA database
Deionized water	Water, deionised {Europe without Switzerland}| market for water, deionised | Cut-off, U	Ecoinvent LCA database
Bishexamethylenetriamine	Hexamethylenediamine {EU-27}| consumption mix	We assume the environmental impact of BHT production is similar to that of hexamethylenediamine (HMD). CarbonMinds LCA Database
Sodium dithionite	Sodium dithionite, anhydrous {RER}| market for sodium dithionite, anhydrous | Cut-off, U	Ecoinvent LCA database
Urea	Urea {RER}| market for urea | Cut-off, U	Ecoinvent LCA database
pMDI	Methylene diphenyl diisocyanate {EU-27}| consumption mix	CarbonMinds database. Environmental impacts of MDI and pMDI are comparable.
Methanol	Methanol {EU-27}| consumption mix	CarbonMinds LCA Database
Ammonium nitrate	Ammonium nitrate {RER}| market for ammonium nitrate | Cut-off, U	Used in adhesive/board production. Ecoinvent LCA database
Wax emulsion	Paraffin {RER}| production	Used in adhesive/board production. Waxes assumed to be based on paraffin. Ecoinvent LCA database.
Water in solutions	Water, deionised, from tap water, at user {Europe without Switzerland}| market for water, deionised, from tap water, at user	Solutions include deionised water. Ecoinvent LCA database
Wood chips	Wood chips, wet, measured as dry mass {Europe without Switzerland}| market for | Cut-off, U	Ecoinvent LCA database
Electricity	Electricity, medium voltage {RER}| market group for	Ecoinvent LCA database
Heat	Heat, district or industrial, other than natural gas {RoW}| heat production, wood chips from industry, at furnace 300kW | Cut-off, U	Ecoinvent LCA database

Abbreviations: RER average European, GLO global, RoW rest of world.