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A.M. López-Contreras, T. de Vrije

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Authors: A.M. López-Contreras, G.J. de Vrije

Institution: Wageningen Food & Biobased Research

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Public final report

1 Summary, basic principles, and objectives

One of the objectives set out in the Renewable Energy Directive II (RED II) is an increase in the use of advanced biofuels in the transport sector to a minimum of 3.5% of all biofuels in the EU. Advanced biofuels are biofuels that are produced using sustainable biomass (described in the RED II, Annex IX) and with significantly lower greenhouse gas (GHG) emissions than fossil fuels. Residual streams from agriculture and the food industry that are produced locally have the potential to serve as raw materials for advanced biofuels. The BioJet Fuel project has mapped the entire value and production chain for biofuel for aviation (sustainable aviation fuel, SAF) made using organic wet waste streams. The results of this project could be a first step in establishing new value chains in the Netherlands, where biomass and residual streams with a high moisture content from primary agriculture and the food industry are used as a starting material for advanced biofuels.
The raw materials used as a model in the project were waste and side streams produced in the processing of potatoes. These streams were used as a starting material for fermentation production of acetone, isopropanol, butanol and ethanol (ABE/IBE fermentation). These residual streams are inexpensive, plentiful, and have a composition that lends itself well to fermentation. In view of their high moisture content, they are not suitable for thermochemical fuel production. The A/IBE fermentation mixture can be directly chemically converted into hydrocarbons and then into aviation fuel after hydrogeneration and fractioning. In this project, the technical aspects of the entire production and value chain for converting wet residual streams from agriculture into fuel were demonstrated through experimental research. In addition, a techno-economic analysis and lifecycle analysis (LCA) of the value chain were also carried out (Figure 1). A potential new application for A/IBE mixtures for the reductive decomposition of lignin into aromatics was also examined, with the aromatics serving as a high-quality additive to fuel.

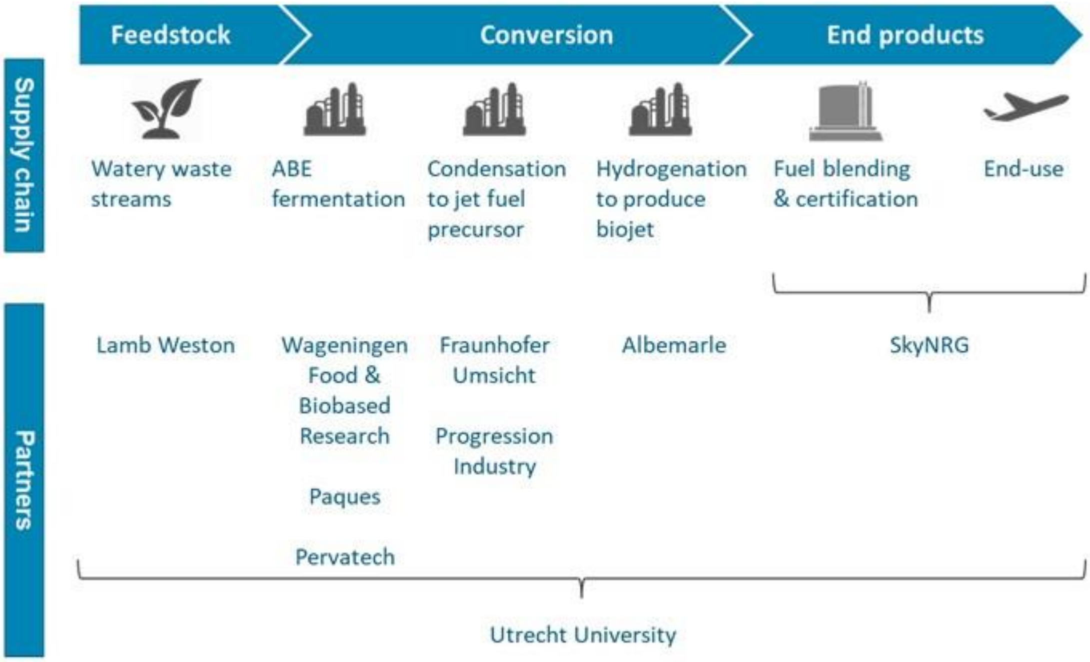


Figure 1 Value chain and partners in the BioJet Fuel project

Goals

The project focused on the value chains for sustainable production of an advanced biofuel for aviation using organic wet residual streams that are available in the Netherlands, using residual streams from potatoes as a raw material model. The ultimate goals of the project were:

- To reduce raw materials and investment costs for the production of biofuel by using low-value biomass and more efficient technologies for fermentation and product reprocessing. This cost reduction can be accomplished through the use of pervaporation as a technology for the separation of product from the fermentation mixture, which represents a more cost-effective technology when compared to distillation.
- Use of the product mixture (A/IBE) as an intermediary fuel. To supply experimental data relating to the production of a potentially interesting and new type of biofuel for aviation.
- To determine the potential reduction in GHG emissions. A study of the market potential of the biofuel and to establish an initial techno-economic evaluation of the new value chain. These studies will form the basis for subsequent activities.

In order to map the complete value chain for a biological aviation fuel, cooperation between companies and research institutions is essential. Members of the consortium were chosen so as to ensure complete coverage of all steps from substrate to final product and so that environmental, economic, and social aspects could all be incorporated into the analysis. These parties are:

- Lamb Weston Meijer as producer of residual streams
- WUR and Paques for fermentation
- Pervatech for reprocessing of fermentation products
- Albemarle for hydrogeneration of hydrocarbons and esters
- SkyNRG and Progression Industry for analysis/testing of biofuel and its components
- Utrecht University for the lifecycle analysis (LCA) and techno-economic analysis (TEA)

2 Results and perspectives for application

Production of biofuel from biomass for use in aviation

Three residual streams from the potato processing process (steam peelings, grey starch, and potato pieces, Figure 2) were tested as a raw material for the production of acetone, butanol, and ethanol by means of fermentation. These streams are rich in starch and sugars and are suitable for fermentation by micro-organisms without the addition of extra nutrients. The three residual streams can be effectively fermented by the anaerobic micro-organisms that produce acetone, butanol, and ethanol. Four different varieties were tested for growth and solvent production on the residual streams on a laboratory scale. Looked at generally, the yields from the products in the laboratory scale fermentations using residual streams were comparable with those in fermentations using pure sugars, i.e. approx. 0.3 g ABE per gram of fermented sugar. The best strain was selected for large-scale fermentation.

Figure 2 Potato residual streams used in the research. From left to right: steam peelings, grey starch, potato pieces. Photographs: Wageningen Food & Biobased Research

For use in a bioreactor, the steam peelings were treated with an enzyme to decompose the starch and thus reduce the viscosity, with the steam peelings then stirred to ensure thorough mixing. This pre-treatment is required only to ensure good mixing in the bioreactor and not for the decomposition process, as the micro-organisms are capable of decomposing the starch themselves. Figure 3A shows a laboratory-scale bioreactor with steam peelings as the raw material.

To upscale the fermentation to 100-L scale, the steam peelings were enzymatically and mechanically pre-treated in order to reduce the viscosity and dry matter content to ensure thorough mixing in the 140-L bioreactor. The mechanical pre-treatment was carried out using a juicer (Angel or slow juicer), which separates the firmer fraction from the liquid fraction, the slurry (Figure 3B). The majority of carbohydrates (92% of the total starch and sugars) are found in the liquid fraction.

To produce enough ABE to create a biofuel, the sugar-rich liquid fraction that was obtained after pre-treatment of the steam peelings was used – this thin slurry could be mixed sufficiently in a 140-L bioreactor. Fermentation of 90 kg of steam peeling slurry (fresh weight) produced a mixture of 0.8 kg acetone, butanol, and ethanol and was subsequently purified from the fermentation liquid (Figure 3C). The related yield of 0.20 g ABE per gram of sugar was lower than anticipated, which could be attributed to the sub-optimal conditions in this pilot fermentation. The high production of the organic acids acetic acid and butyric acid indicates potential stress conditions for the micro-organisms during fermentation. In a subsequent project, there will be a greater focus on the upscaling of the fermentation of the slurry material, particularly on optimal mixing in the bioreactor. A high-protein fraction from microbial cells and non-fermented substrate was the most important by-product in solid matter from fermentation. This fraction contains vitamin B12 and could potentially be used as an animal feed supplement. Other by-products were H_2 and CO_2, both of which can be sold for various uses and, in the former case, can be used in the production of aviation fuel.

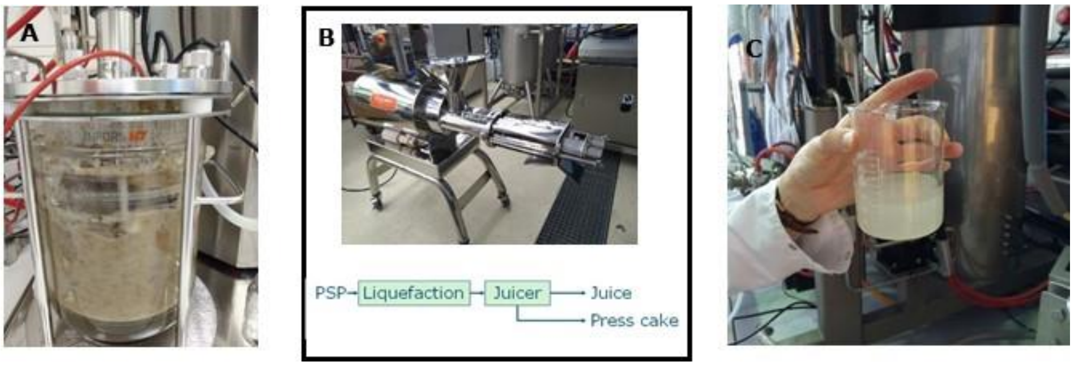


Figure 3 ***A. Bioreactor with steam peelings as a raw material; B. Photograph of the juicer (Angel juicer 140K) used in the pre-treatment of the steam peelings for the pilot fermentation and diagram of the process. PSP, potato steam peelings; C. Condensed fermentation product from the pilot fermentation. Photographs: Wageningen Food & Biobased Research***

The presence of anaerobic micro-organisms in the substrates was analysed by means of genome sequencing of the microbiome in samples taken from each residual stream. In the three untreated residual streams, micro-organisms capable of producing acetone, butanol, and ethanol themselves were demonstrated in significant quantities. This opens up opportunities for the development of non-sterile processes, whereby fermentation into biofuel components is carried out by endogenous flora from the residual streams (own microbiome), with a significant reduction in costs when compared to standard sterile fermentation processes. This topic can be developed further in a subsequent project. The ABE produced from steam peelings was used for condensation in a chemo-catalytic process after separation of the fermentation liquid, with mixtures of oxygenated hydrocarbons being the product (Figure 4, Fraunhofer Umsicht). For use as an aviation fuel, an additional step is needed – hydrogenation, whereby the oxygen elements are removed to leave pure hydrocarbons. The hydrogenation of the condensation product was carried out under standard conditions for comparable biofuels. The result was a clear liquid that was analysed for relevant properties needed to allow for use as an aviation fuel (Figure 4).

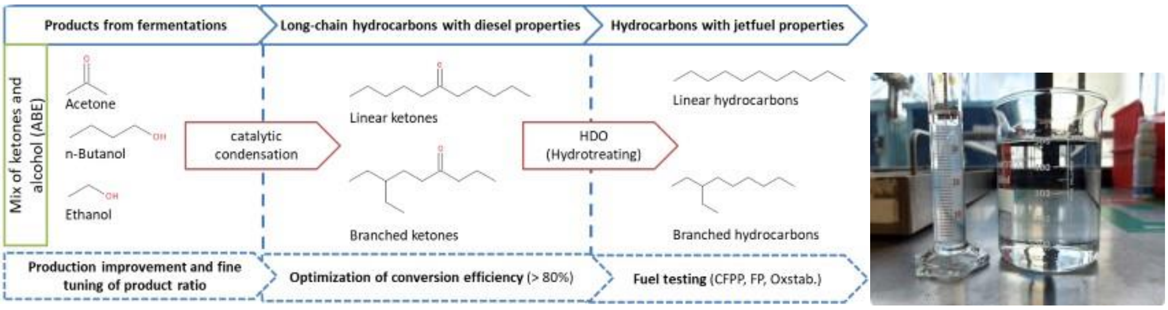


Figure 4 ***Diagram of the catalytic conversion of acetone, butanol, and ethanol mixtures in biofuel for aviation (Fraunhofer Umsicht technology, left) and photograph of a sample of the end product after hydrogenation (right). Photo: Albemarle***

The quality of the liquid produced was analysed according to the requirements of the American Society for Testing and Materials (ASTM) for new fuels. The analysis showed that there is potential as a biofuel, without the addition of aromatic components. The product does not currently satisfy all requirements for aviation fuel, as the sample was produced on a laboratory scale and the limited volume could not be effectively upgraded as a result. Optimisation of some of the steps in the production process, and addition of a final distillation step, are required in order to reduce the number of impurities and thus achieve a high-quality product.

The polymerisation of lignin to aromatic components was tested as an alternative to or as a supplementary use of acetone, butanol, and ethanol mixtures in the production of biofuel components. Exploratory testing with different lignins was carried out in order to obtain aromatic-rich fractions by means of Hydrous Thermal Depolymerisation (HTD) with ABE as the solvent. The best results were achieved with Soda P-1000 lignin. This application is still in the very early stages of development and further research needs to be conducted to advance development Of this route.

Sustainability and economic evaluation of the new value chain

The sustainability and economic feasibility of the new value chain were evaluated by means of an initial techno-economic analysis (TEA) of the different steps in the chain and a lifecycle analysis (LCA). Two scenarios were studied for these analyses (Figure 5):

a. Central processing of the biomass and production of the biofuel at a single location.
b. Decentralised processing of the biomass into ABE at the production location followed by further production to create biofuel at a central location.

The Port of Rotterdam was chosen as the central location for production of the biofuel as it possesses the infrastructure required for both the supply of raw materials and the distribution of the biofuel.

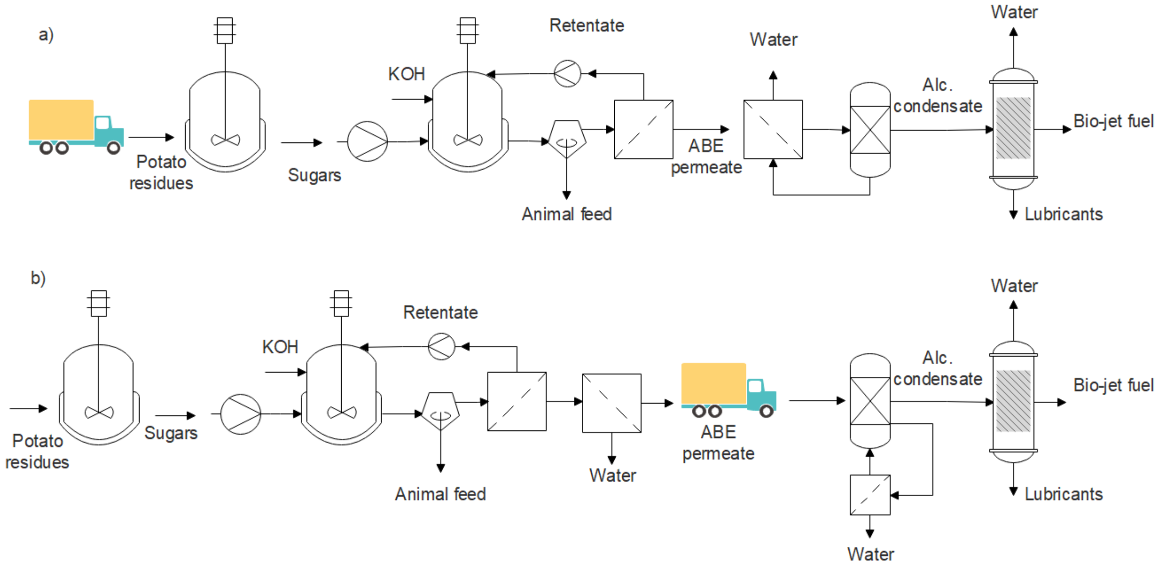


Figure 5 ***Diagrams of the value chains for production of biofuel from potato residual streams. a) Central processing and production of biofuel; b) Decentralised processing of the biomass into ABE at the production location followed by production of the biofuel at a central location. Source: Moretti et al. (2020)***

Conclusions from the TEA and LCA analyses

- The cost price is not competitive with existing SAFs produced using the HEFA process as the production process is very complex. As BioJet produces fuel using lower grade raw materials than HEFA and more processing steps are needed to achieve a high-quality aviation fuel as a result, the processing costs are higher. In general, the cost price of biofuel from potato residual streams is comparable with the price of other alcohol-based biofuels produced using residual streams.
- The cost price of a biofuel produced with a ‘central value chain’ (Figure 5a) is more favourable thanks to the option to use the hydrogen produced for hydrogenation, CO_2 storage, and a lower CAPEX thanks to upscaling.
- Well-to-Wheel (WTW) estimation: a 50% GHG reduction when compared with conventional kerosene, we see potential to optimise the production process and to improve reductions in GHG so that a minimum GHG reduction of 65% can be achieved.

Process improvements and points for attention

The following process improvements and points for attention could form the basis for subsequent research:

- Use of locally available raw materials, perhaps in combination (multi-raw material process), that satisfy the RED sustainability criteria and are available in sufficient volume.
- Cost reduction in the fermentation process by:
  - Applying non-sterile conditions (use of microbiome in the raw material) in new-type bioreactors related to the current technology for waste water treatment (Figure 6)
  - More efficient recovery of products, primarily acetone, from the fermentation medium
  - Higher yields per kg of raw material
  - Marketing of by-products, such as microbial biomass as a source for high-quality ingredients
- Optimisation of the chemo-catalytic steps, condensation, and hydrogenation
- A further reduction in the carbon footprint through reduced energy consumption, reuse of produced carbon dioxide
- Production of a sufficient volume of biofuel for extensive technical ASTM and engine testing

Figure 6 ***Examples of water treatment systems based on the Paques technology. Photographs: Paques BV***

Perspective for application

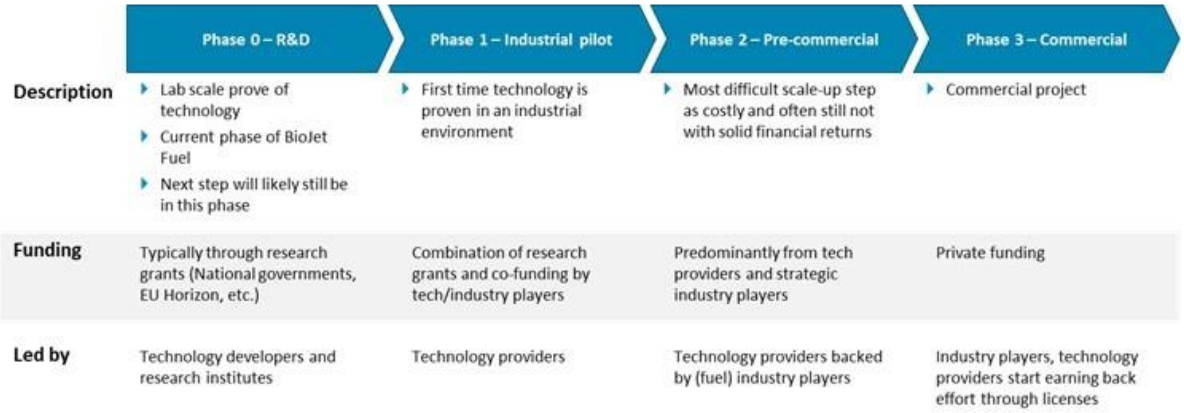
Quality of the product

The new value chain for the production of aviation fuel from wet residual streams was investigated in the project as a proof-of-principle, and the results appear promising. In terms of its chemical composition, the fuel is similar to existing SAFs and is relatively rich in cyclo-paraffins. The fuel is expected to satisfy the important aviation fuel parameters, such as the distillation curve, flash point, density, freezing point, and viscosity as soon as larger volumes can be produced, which will specifically allow for the jet cut to be distilled.

The next steps

This route requires further development for it to be applicable on commercial scale. A number of steps are foreseen for further development of this value chain (Figure 7):

- Phase 0 (follow-up R&D project), where sufficient quantities of the biofuel can be produced and the technologies can be further developed in order to improve production costs and reduce GHG further.
- Phase 1 (industrial pilot) - Phase 2 (pre-commercial). Once step 1 is completed, an operational pilot can begin, with the involvement of market parties. The procedure for ASTM approval of biofuel can be commenced, in parallel with the initial fuel tests.



	Phase 0 – R&D	Phase 1 – Industrial pilot	Phase 2 – Pre-commercial	Phase 3 – Commercial
Description	Lab scale prove of technology Current phase of BioJet Fuel Next step will likely still be in this phase	First time technology is proven in an industrial environment	Most difficult scale-up step as costly and often still not with solid financial returns	Commercial project
Funding	Typically through research grants (National governments, EU Horizon, etc.)	Combination of research grants and co-funding by tech/industry players	Predominantly from tech providers and strategic industry players	Private funding
Led by	Technology developers and research institutes	Technology providers	Technology providers backed by (fuel) industry players	Industry players, technology providers start earning back effort through licenses

***Figure 7	Phases leading to commercialisation of the BioJet Fuel route***

3 Contribution of the project to the objectives of the program

By 2050, the aviation industry will produce between 3 and 5% of global carbon emissions, despite anticipated efficiency improvements in aircraft and aviation processes. Estimated current fuel consumption in the EU is 53 Mt per year, with CO_2 emissions of 167 Mt. Within the ReFuel EU Aviation Initiative, the European Commission is discussing the possibility of establishing a mandate for the use of sustainable aviation fuel in order to minimise CO_2 emissions from air transport and thereby contribute to achieving the EU’s climate targets. Production of sustainable aviation fuel is subject to stringent sustainability requirements, as outlined in REDII, whereby a new SAF production facility must be able to realise a CO_2 reduction of at least 65%. There are not currently sufficient production facilities to be able to achieve the EU’s goals, plus there is also a shortage of raw materials for the production of SAF with existing technologies. Consequently, the development of new production routes and raw materials combinations is essential to meet the EU’s goals.

The results of this project show an alternative route for SAF production, based on organic wet residual streams that are available in the Netherlands. The biofuel produced in the project has potential as an SAF, demonstrated in an initial round of analytic tests in accordance with ASTM protocols. The SAF is rich in cyclo-paraffins and is therefore an attractive synthetic blend component.
The first lifecycle analysis (LCA) of this route shows a reduction in GHG of 50% when compared to fossil kerosene. This reduction is not yet sufficient to satisfy the sustainability target in the REDII, but there are number of steps in the process, whereby further developments could achieve a potential reduction of more than 65% in a subsequent process.

The value chain developed in this project is a step forwards in the development of alternative SAF in the Netherlands. A number of Dutch organisations, namely SkyNRG, Albemarle, Paques, Lamb Weston Meijer, Progression Industry and Pervatech, collaborated with Wageningen University & Research and Fraunhofer Umsicht (as a subcontractor of WUR) in this project to develop this new process. These parties see opportunities for further development in a subsequent process.

4 Publications about the project

Project page in WUR: https://www.wur.nl/nl/project/BioJet-Fuel-project-stimuleert-de-productie-van-biobased-vliegtuigbrandstof.htm

Oral presentation by P.A.M. Claassen, WFBR. 'Microbial conversion of biomass' by P.A.M. Claassen, T. de Vrije, A.M. López Contreras. BIT's 3rd International Biotechnology Congress-2019, 25-27 October 2019 in Singapore http://www.bitcongress.com/IBC2019/

Poster presentation by Christian Moretti, Utrecht University:
'Techno Economic Analysis and Life Cycle Greenhouse Gas Emissions of a Novel Aviation Fuel from Residue Streams from the Potato Processing Industry"' by Moretti C, López Contreras A M, de Vrije T, Kraft A, Junginger M, Shen L. e-EUBCE 6-9 July, 2020, virtual 28th European Biomass Conference http://www.etaflorence.it/proceedings/

Scientific article: 'From agricultural (by-)products to jet fuels: carbon footprint and economic performance' (2021) by Moretti et al,
https://www.sciencedirect.com/science/article/pii/S0048969721009153

With contributions from:

C. Moretti, L. Shen (UU); C. Frijters (Paques); T. de Vrije, H. van der Wal, A.M. López Contreras, M. Werten, R. Veloo, A. van Zeeland, J. van der Putten, G. Frissen, D. van Es, J. van Haveren, R. Gosselink (WFBR); T. Arts (PI); S. Wibowo (LW), I. Lammerink, F. Velterop (PV); M. Peters, A. Menne, A. Kraft (FU); R. van Duren, M. Koch, L. Boot (ALB), E. van Mastbergen, O. Meijerink (SkyNRG)

Project partners

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Contact person for further information

Contact person:
Ana M. López Contreras
E: ana.lopez-contreras@wur.nl
Wageningen Food & Biobased Research
Bornse Weilanden 9, 6708 WG Wageningen, the Netherlands
Wageningen Campus I Building 118 (Axis)

To explore
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of nature to
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Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
E info.wfbr@wur.nl
wur.nl/wfbr

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