agriloop

high-value products from agricultural residues through sustainable chains

Project number: 101081776

Deliverable D1.9

Framework for Early Sustainability Guidance

Workpackage(s) concerned: WP1

Workpackage leader: Jan Broeze

Deliverable Leader: SDU

EC Version: 1.0

Planned delivery date (as in DoA): 30/11/2024 (24)

Actual submission date: 20/12/2024, (25)

Funded by the European Union

UK Research and Innovation

Project funded by Schweizerische Eidgenossenschaft, Confédération suisse, Confederazione Svizzera, Confederaziun svizra, Swiss Confederation — Federal Department of Economic Affairs, Education and Research EAER, State Secretariat for Education, Research and Innovation SERI

中华人民共和国科学技术部 Ministry of Science and Technology of the People's Republic of China

Table of contents

This project has received funding from the European Union's Horizon Europe research and innovation programme under the grant agreement No. 101081776, the UK Research and Innovation (UKRI) fund under the UK government's Horizon Europe funding guarantee, the Swiss State Secretariat for Education, Research and Innovation (SERI) and from the National Key Research and Development Program of China (NKRDPC). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of neither of the aforementioned Funding authorities. Neither the European Union, the United Kingdom, the Swiss Confederation or the People's Republic of China nor the European Commission, UKRI, SERI or NKRDPC can be held responsible for them.

Dissemination Level

P	*Public*	☒
CO	*Confidential, only for members of the consortium (including the Commission Services)*	☐
CI	*Classified, as referred to Commission Decision 2001/844/EC*	☐
SEN	*Sensitive*	☐

Type

R	Document, Report	☒
DEM	Demonstrator, Pilot, Prototype	☐
DEC	Websites, Patent Fillings, Videos, etc	☐
Other	(Please describe the type)	☐

Project Number: 10108176

Project: AgriLoop : pushing the frontier of circular agriculture by converting residues into novel economic, social and environmental opportunities

Topic: HORIZON-CL6-2022-CIRCBIO-01-05

Duration: 48 Months

Start date of Project: 1st December 2022

End date of the Project: 30 November 2026

Coordinator: INRAE

Deliverable: D1.9

Due date of deliverable: 30.11.2024

Actual submission date: 30.12.2024

Work package number: WP1

WP Leader (name and organisation): Jan Broeze (WR)

Person in charge of the deliverable (name and organisation): Benyamin Khoshnevisan (SDU)

Author(s): Mias Sommer Schjønberg (SDU)

Contributor(s): Duman Kamalebieke (SDU); Benyamin Khoshnevisan (SDU), Morten Birkved (SDU)

Version: 1.0

1. Executive Summary

To fulfill the objectives of AgriLoop Task 1.4, SDU has developed a framework for early assessment of the technologies being developed by AgriLoop partners to provide estimates on the sustainability impacts for selected pathways. To this end, SDU selected four pathways that all utilize tomato waste, to ensure comparability. Initial estimates indicate that there is significant room for improvement in the sustainability of the technologies.

The framework proposed by SDU is based on five key principles. Firstly, it emphasizes consequential impact assessments to understand the ripple effects of AgriLoop's processes across multiple markets. Secondly, it ensures accurate comparisons by defining functional units based on input materials. Thirdly, the framework supports multiple scenarios to account for changes and scale-ups over time. Fourthly, it uses prospective life cycle assessment (pLCA) to predict future environmental impacts. Finally, it ensures verifiable claims through open-source software and transparent data processing methods. The framework and accompanying software have been developed with reuse in mind and are compatible with future datasets both within the scope of AgriLoop and in future projects.

Four value chains were selected for early assessment: polyphenol extraction from tomato peels by INRAE, PHA production from tomato pomace by NID, cutin extraction from tomato skins by TomaPaint, and peptide extraction from tomato seeds by UNIBO. The assessments showed varying impacts across different processes, with some indicating significant room for improvement. Detailed analysis identified key impact hotspots, such as chemical consumption and energy requirements.

Addressing the identified hotspots, such as the high consumption of chemicals in INRAE's process and the significant energy requirements in UNIBO's process, could substantially enhance the environmental efficiency of these technologies. By optimizing these areas, the AgriLoop processes could become more competitive versus the current methods of tomato waste processing. It is important to note that the processes explored in this assessment are not mutually exclusive, and as such even individual process optimizations can potentially lead to overall more efficient waste valorization pathways.

TABLE 1 – ABBREVIATIONS

ABBREVIATION	DEFINITION
LCA	Life Cycle Assessment

PHA	Polyhydroxyalkanoate
PHB	Polyhydroxybutyrate
GWP	Global Warming Potential
NR	Natural Resource Depletion

2. Introduction

In order to understand the state of the art of life cycle assessment (LCA) in waste valorization, we performed a literature review on the valorization of biowaste into polyhydroxyalkanoates, or PHA – a type of biodegradable plastic that can be produced by processing various types of wastes, including agricultural, with bacteria. PHA specifically was selected as the topic of the review as the production of such plastics is becoming increasingly more relevant in today's society, its comparability to existing plastics on the market, and due to its relevance as a potential output of AgriLoop processes. A sub-category of PHA, polyhydroxybutyrate (PHB), has also been referred to independently in literature and as such as included as its own search term in the review. The search was conducted through Web of Science and Scopus, using the keywords "life cycle assessment", "life cycle analysis", "PHA", "PHB", "polyhydroxybutyrate", and "polyhydroxyalkanoate".

After filtering for duplicates, the search returned 195 studies. 67 of these studies were found to be topically irrelevant (typically due to shared acronyms with other fields of research), resulting in 124 relevant studies. Between the years of 2019 and 2024, after manually filtering to remove reviews, conference proceedings, etc. 43 case studies assessing aspects of the environmental life cycle performance of PHA were identified.

PHA and PHB were studied with relatively equal frequency at 24 and 18 studies respectively. Of these studies, only 17 studies focused on agricultural waste with the remainder primarily analyzing waste processing for the organic fraction of municipal solid waste (OFMSW) or wastewater (WW) treatment. Furthermore, 25 of the total studies listed their functional unit based on output while 9 used the incoming waste and residuals as their functional unit (FU), indicating there is ongoing discussion as to whether the production of plastics from wastes should be considered a production process or as a waste treatment process.

The most frequently performed system boundaries assessed were cradle-to-gate of which there were 23, followed by cradle-to-grave and gate-to-gate with 9 and 6 studies performed respectively. While many of the studies were unclear in their system boundaries, 6 specified the usage of consequential databases while 2 make specific reference to displaced end products and energy demands but do not directly indicate if these are LCAs performed with consequential databases or attributional LCAs with only foreground market displacement considered.[1, 2].

Furthermore, the versions of the inventory database ecoinvent used in reviewed literature vary dramatically, from version 3.9.1 all the way down to version 2 – though in many cases the specific version was not mentioned at all. Most notable changes to the ecoinvent database include the addition of many of the agricultural products considered by AgriLoop in ecoinvent 3.3, the addition of plastic recycling technologies (specifically PE and PET) in ecoinvent 3.4, and the dramatic increase in waste treatment processes and country-specific municipal waste composition in ecoinvent 3.5[1]. The historical data gap created by ecoinvent is also exacerbated due to many current studies relying on results from LCAs performed on PHA production dating back to as early as 2003. Due to changes in energy infrastructure, emissions policies, and technological advances the results of these studies may not be entirely comparable to current evaluations.

Yet another difficulty in assessing the performance of various methods of PHA and PHB production lie in result reporting – in several instances results were presented either as relative increases and decreases compared to other options in the study [3]; or no numerical values were given, only plotted on graphs [4-7]. Because of the lack of specific numerical reporting, the results of the studies cannot be used in external comparisons or cited as literature values as the comparison baseline is not readily available.

[1] https://support.ecoinvent.org/

Finally, only four of the studies performed prospective LCAs (pLCA). pLCA is a method by which background systems are modeled to reflect how they are likely to exist in the future including market share of technologies, improvements in said technologies' emissions, etc. pLCA can be performed through the manual development of prospective background systems, or through the use of software such *as premise* [8]. Decisions informed by LCA must consider long-term consequences of the decisions, as they both take time to implement; as well as hopefully exist in the market for an extended period of time, for example, the construction of a biorefinery and its outputs will not only have an impact in the year 2024, but also ten and twenty years into the future.

The literature review has revealed several gaps in the data and methodology of LCAs performed on PHA/B production, especially from agricultural residues. It is in light of this that SDU proposes a new framework for the assessment of the impacts of not only AgriLoop's bioplastic production processes, but of any process that can be modeled using ecoinvent – both AgriLoop and beyond.

SDU's Framework Proposal

SDU proposes an assessment framework based on five principles, which will each be expanded upon below:

1. Consequential impact assessments
2. Uniform functional unit definition.
3. Flexibility to support foreground processes changing in future scenarios.
4. A dynamic, prospective model to account for the technological advancements of the background systems.
5. Transparent, reproducible, and open data processing.

Consequential impact assessments

AgriLoop is an ambitious project with goals of agricultural waste valorization both in the EU and in China. As such, the impacts of AgriLoop's developed processes will be far-reaching across multiple markets – both for the output products as well as the agricultural residue inputs. To gain a complete understanding of this ripple effect, consequential modeling is necessary, as it encompasses the impacts incurred by both the consumption of resources as well as the impacts avoided by taking those resources away from other processes.

Waste Treatment Processes

Strict definition of a FU allows for proper and adequate comparisons and empowers decision makers to make the most informed choices. Therefore, it is especially critical for a project with the scope and size of AgriLoop's to properly define FUs such that results can be compared accurately; a task made more difficult due to the numerous processes being developed of which many outputs may not have comparable end uses, such as a kilogram of phenols vs. a kilogram of cutin.

To fairly compare every potential value chain created in AgriLoop, they must be modeled as the impacts of any given input, e.g. "the impacts incurred by processing one kilo of tomato pomace". This also reduces confusion that could arise when multiple separate residues can be utilized towards them same end. For example, both tomato and potato peels can be used as feedstocks to produce PHA precursors, though requiring different quantities of input. This would then lead to two PHA impact assessments with drastically different results and the implication that the decision maker selects which option they prefer – when in actuality they are not mutually exclusive. By defining the functional unit as a kilogram of input material, the final impacts reported are more likely than not mutually exclusive and can answer the question, "with a finite supply of waste annually, which treatment route performs the best environmentally?".

Flexibility

Processes in LCA calculations, especially those of low TRL and under active development, are not final. Operation parameters can change, as can yields and waste flows. A given waste treatment process may only be optimal for a few years until a state-of-the-art biorefinery can be constructed. Therefore, the support of multiple scenarios to account for changes and scale-ups over time is necessary.

Prospective Modeling

The processes developed in AgriLoop and the decisions based on them will not be singular actions with one-time impacts – they will (hopefully) lead to the development of waste management processes that will persist for years to come. As a result, an understanding of what the environmental impacts of those results will be in the distant future is critical to making the right decision now. Through the use of pLCA software like *premise* [8], we have the ability to generate prospective versions of ecoinvent to assess the performance of AgriLoop processes in future scenarios and contexts, with background systems calculated based on projected technological advances and market share changes.

Open and Transparent Data Processing

In order to make verifiable claims about the environmental impact of AgriLoop processes for decision-making not only must all results be presented both visually and numerically either in a report or in its supplementary information, but the process by which they've been calculated must be made available as well.

SDU has developed software to calculate environmental impacts with these five principles in mind called *F*lexible *A*utomatio*N* of life *CY*cle assessment, or "*Fancy*". The source code will be available as open-source Python software upon publication on the code sharing repository GitHub at https://github.com/igt-misc/fancy_lca. *Fancy* is also not a solution limited to the specific field of bioplastic impacts; it is fully generic – meaning it can be applied not only to every process within AgriLoop but to any process built using an ecoinvent database. Because of this, not only will the results be replicable and comparable, but they will also be available for future reference by other projects and will lay the baseline for understanding the impacts of current, state-of-the-art agricultural residue waste valorization value chains.

3. Early Sustainability Framework – *Fancy*

Fancy is developed in Python 3.11 and works as an integration between three open-source LCA software packages: openLCA [9] and Brightway [10], as well as *premise* [8], and utilizes the life cycle inventory database ecoinvent [11]. It must be noted that ecoinvent is closed-source and requires a license – however, neither *Fancy*, openLCA, Brightway, nor *premise* are dependent on it and can feasibly be used in conjunction with a different, open database.

The ecoinvent database is a well-documented, industry standard database containing the environmental impact data for processes spanning such industries as electricity production, mining, manufacturing, agriculture, and more. When calculating the environmental impact of a given process, not only are the direct emissions of the process (i.e., the 'foreground system') required, but also those of the infrastructure utilized (i.e., the 'background system'). This includes the consumption of electricity, transport emissions for shipping wares via lorry or ship, processing waste materials, etc. While foreground systems are typically constructed via firsthand data collection and literature estimates, background systems are often far too complex and data-intensive to be feasible. Therefore, databases such as ecoinvent are utilized.

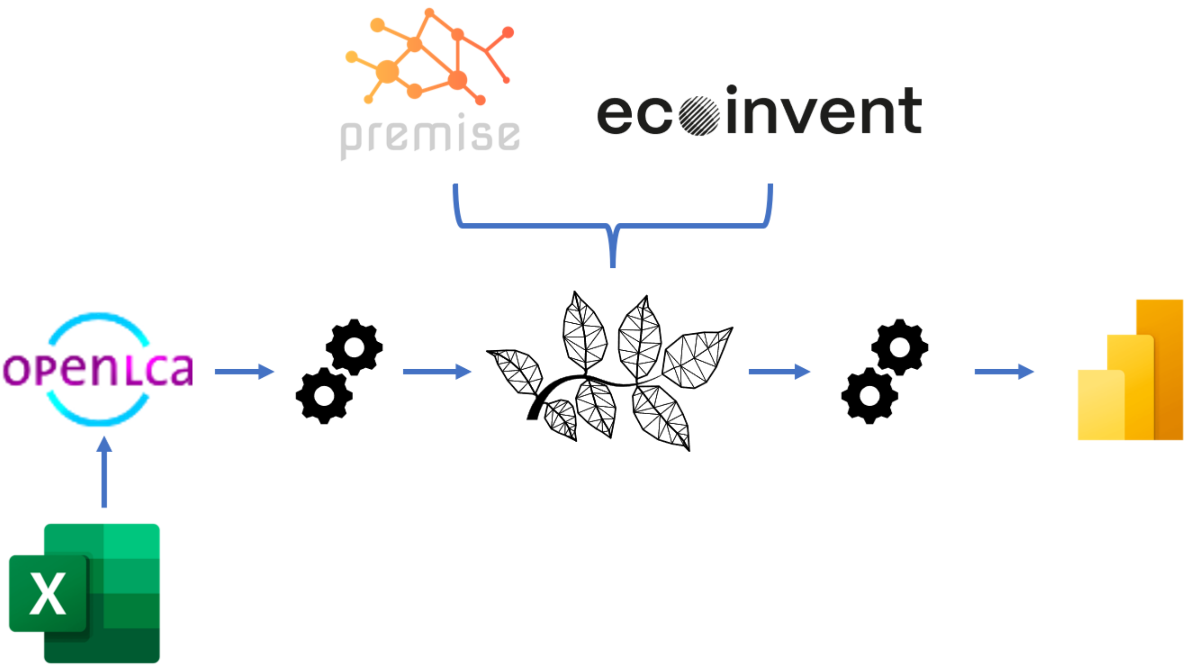

FIGURE 1 - *FANCY'S* WORKFLOW

openLCA is open-source software used to calculate the environmental impacts of products or services. It is used in conjunction with background databases and provides a user interface for performing LCAs. In the context of *Fancy*, it is used primarily as an interface for the user to construct their foreground system. This is to ensure users who aren't skilled in programming can use the *Fancy* as well. After the foreground system is built as processes in openLCA, the required amount of each process/product/service is given a placeholder parameter value. These parameter values are filled in in an Excel sheet and given values for each potential scenario, for example: one scenario could use 10% less raw material and 5% more electricity while another one uses 15% more raw materials but consumes 10% less electricity. This data is then processed using Brightway.

Brightway is open-source LCA software similar to openLCA, though with two key differences: it is purely programmatic with no graphical interface, meaning to use it one must be familiar with Python development; and offers much more flexibility over openLCA in how calculations can be performed and how results can be delivered. Brightway is also fully compatible with ecoinvent, meaning it can perform the same calculations on the same datasets as openLCA does. However, due to Brightway being fully Python, it allows for far more fine-grained control over the impacts calculated, more flexible automation, and far more robust data processing. Finally, unlike openLCA, Brightway is compatible with *premise*, the state of the art software used for calculating prospective LCAs.

Premise is open-source software used to generate prospective databases in conjunction with ecoinvent. *premise* functions by transforming ecoinvent to reflect projected future scenarios as defined by IAMs, or 'integrated assessment models'. IAMs are mathematical models of regional and global social-, economic-, and technological development based on the Shared Socioeconomic Pathways (SSPs), a set of scenarios defining various potential futures for society globally in the context of climate change [12]. For the purposes of AgriLoop, we have selected to use the REMIND IAM [13] as it has the largest coverage of SSPs over other compatible IAMs as it is the only one to include models for SSP5. We have elected to generate prospective databases for the years 2030, 2040, and 2050 for SSPs 1, 2, and 5. These pathways reflect society developing via a dramatic shift to renewable energy, business as usual, or with continued use of fossil fuels respectively. Each of these SSPs then has variations called Representative Concentration Pathways (RCPs), where the SSP background systems are modeled to reflect how they could meet specific global warming targets. For these, we have elected to use the Base version (only the SSP), as well as two Paris Climate Agreement RPCs. The Paris Climate Agreement RPCs were chosen as they are commonly used when utilizing *premise*.

To summarize, when the end user runs the code, *Fancy* will translate the Excel files and openLCA processes into Brightway activities, and then perform the life cycle inventory calculations for the present day. After this, it repeats the process for each scenario defined in the Excel sheet and when finished it repeats the process again for each SSP/RCP database generated using *premise,* for each year selected. Furthermore, *Fancy* currently performs contribution analysis at one layer of depth, meaning not only does *Fancy* return the impacts of the process itself, but also the impacts of each direct input process. Future development will enable user-specified recursion depths for contribution analysis. Finally, all outputs are saved back as Excel files which can then be imported into (for example) PowerBI, Microsoft's business analytics software, for analysis.

By doing this, we have developed a pipeline wherein all calculations can be batched and performed simultaneously, dramatically streamlining the iterative process of LCA . The outputs are formatted such that they can be directly imported into PowerBI for immediate analysis and slicing based on process, impact categories, SSP, year, and each process' own scenarios.

Further configuration details can be found in the Github repository.

Process Selection

After reviewing the data received from the AgriLoop project partners, a subset of value chains was selected for early assessment. These value chains are as follows:

- INRAE – Polyphenol extraction from tomato peels
- NID – PHA production from tomato pomace
- TomaPaint – Cutin extraction from tomato skins
- UNIBO – Peptide extraction from tomato seeds

For each of these processes, it was necessary to make background system assumptions due to Ecoinvent 3.9.1 lacking specific data for chemical products. Furthermore, to determine the savings of each product it was necessary to determine what impacts were being avoided by the respective products being produced by the systems. Each process' output was modeled with the most similar substance available in Ecoivent and may not represent the exact impacts being avoided.

Reference Case

In order to provide thorough early assessments, the impacts of the analyzed processes were also compared to the impacts of existing methods of processing tomato waste. As Ecoinvent lacks data referring to tomato waste processing, substitutions were made. Using the data provided in D1.1[2] we modeled the reference system as follows:

- Lycopene production (as soybean meal): 40%
- Animal feed (as soybean feed): 25%
- Bioethanol production (as ethyl tert-butyl ether): 15%
- Biogas production (as biogas, from grass): 15%
- Composting (as treatment of kitchen waste, home composting): 5%

Exact conversion rates were derived using the ResiduesAvailabilityCompositionConversions.xlsx Excel sheet found on the AgriLoop SharePoint. This file will not be included in the supplementary data as it is confidential and for internal use only.

Assumptions

All electricity consumption was modelled using European market averages. This is to account for the fact that these are low TRL technologies being developed across Europe and to control for emissions from energy across the different geographical regions where the research is being conducted. In order to maintain an equal assessment, TomaPaint's pilot plant was also modeled with European market averages.

All water consumed by processes was assumed to be deionized water unless specified to be ultrapure (as was the case with UNIBO).

Energy requirements for heating was calculated by hand, using the specific heat capacity of the primary liquid being heated:

- INRAE: Due to a lack of data on the specific heat capacity of the deep eutectic solvent (DES) used in the process, the value for water (4.18 J $g^{-1}C^{-1}$) was used in calculations. This is an estimation at best, as the constituent components of INRAE's DES are choline chloride and lactic acid, which have specific heat capacities of 1.8 and 127.6 J $g^{-1}C^{-1}$ respectively.
- NID: For the extraction step, the specific heat capacity of hexane (2.26 J $g^{-1}C^{-1}$) was used; for the fermentation step the value for water was used.
- TomaPaint: For all cases it was assumed the primary liquid was water.
- UNIBO: For all cases it was assumed that the primary liquid was water.

All processes were assumed to have the same heat loss over time of 10W.

All solutions, unless otherwise specified, were calculated to be 1N using deionized water.

In many cases ranges for values were given as opposed to specific values. In these instances, the results were calculated using the average of these ranges.

[2] AgriLoop D1.1, and follow-up correspondence with DSS+

INRAE Assumptions

Ecoinvent 3.9.1 does not have production values for choline chloride. Therefore, it was substituted for the generic “chemicals, organic”. The output product of INRAE’s value chain, “polyphenols”, was calculated as substituting “phenolic resin”.

NID Assumptions

Potassium as KH2PO4 and hydrogen phosphate as K2HPO4 were modeled as “chemical, inorganic”. Ammonium phosphate was modeled as “monoammonium phosphate”. The final product of PHA was assumed to substitute “polyethylene terephthalate, granulate, amorphous”.

TomaPaint Assumptions

“Soda” was assumed to be “soda ash, light” and “deionized water”, at 1N. Cutin was determined to substitute “polyester-complexed starch biopolymer” in the market.

UNIBO Assumptions

“Trypsin” was modeled as “chemical, organic”. As UNIBO specified MilliQ water, their water consumption was modeled as “water, ultrapure”. UNIBO’s outputs were modeled as “whey”.

Impact Assessment Methods and Database

For the calculation of impacts, all 256 ReCiPe 2016 Midpoint and Endpoint indicators were used. In the next section the Global Warming Potential (GWP) and Natural Resource Depletion (NR) impacts will be presented, however the full results of all indicators can be found in the supplementary files, as well as a visualization of a very limited slice of this in Annex II.

The database used for background data was Ecoinvent 3.9.1 consequential. This was used in conjunction with *premise* to generate databases for the years 2030, 2040, and 2050; with SSPs 1, 2, and 5; and for the Baseline, PkBudg1150 and PkBudg500 RCPs. For more information on *premise*, SSPs, and RCPs, see Sacchi, et al. [8] For the specific *premise* configuration used for this report, see the supplementary files.

4. Results

Overall Results

All processes were modeled as processing 1kg of tomato waste, as the volume of waste is the limiting factor in production quantities. ".Reference" refers to the existing tomato waste processing pathways.

All diagrams have the same legend, where points are color-coded by SSP/RCP. All results will be shown as box-and-whisker plots, where the bars represent the upper and lower bounds of the data, and the shaded boxes representing the middle 50% of the data points (the second and third quartiles) for ease of reading.

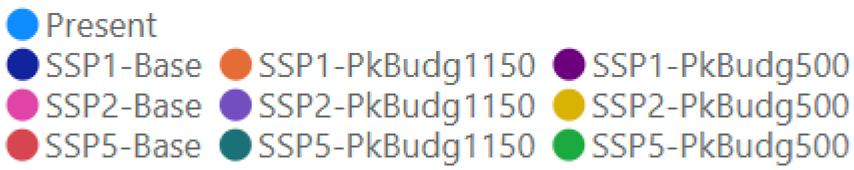

FIGURE 2 - SHARED LEGEND FOR ALL DIAGRAMS. POINTS ARE COLOR-CODED BY SSP/RCP COMBINATION.

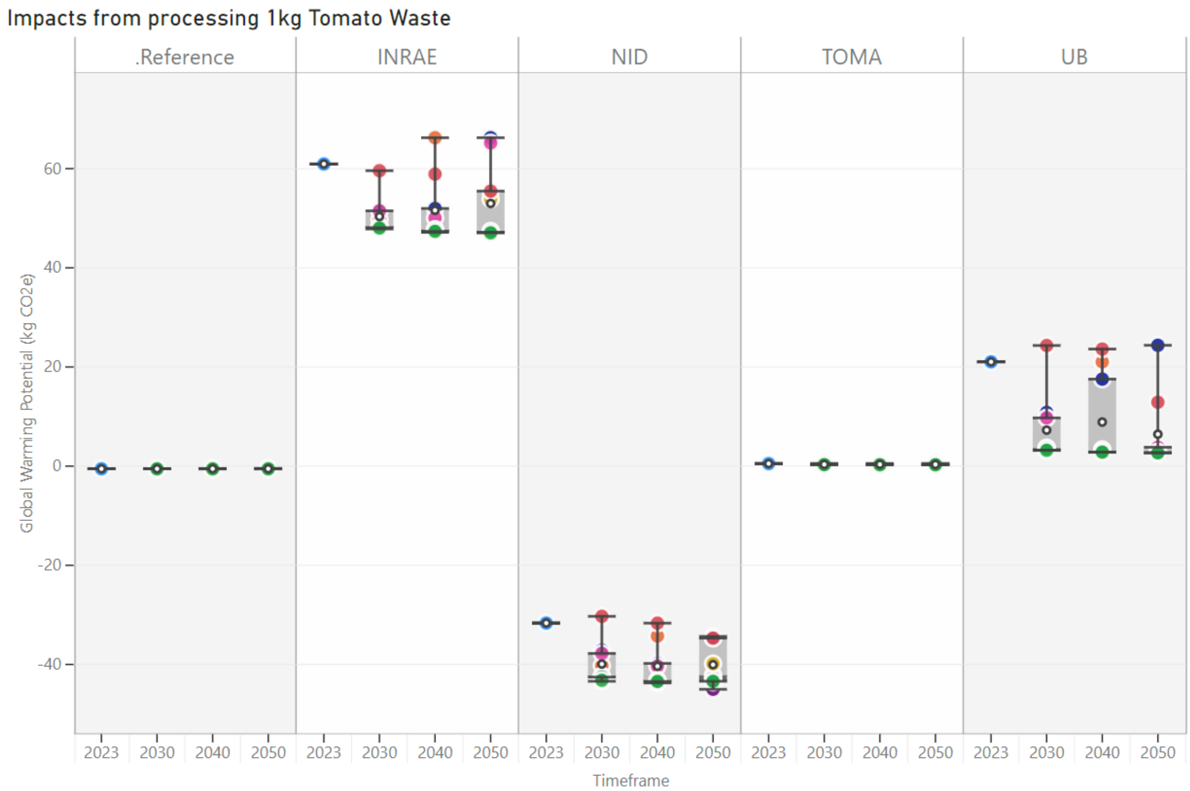

FIGURE 3 - CUMULATIVE GWP100 (RECIPE MIDPOINT (H)): THIS BOX-AND-WHISKER DIAGRAM SHOWS THE CUMULATIVE GWP100 OF THE PROCESSING PATHWAYS PROPOSED BY THE PROJECT PARTNERS INRAE, NID, TOMA, AND UNIBO (UB). '.REFERENCE' REFERS TO THE AVERAGE MARKET MIXTURE OF CURRENT TOMATO WASTE TREATMENT. EACH COLORED DOT REPRESENTS A THE IMPACT VALUES CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN KG CO2E PER 1 KG PROCESSED TOMATO WASTE.

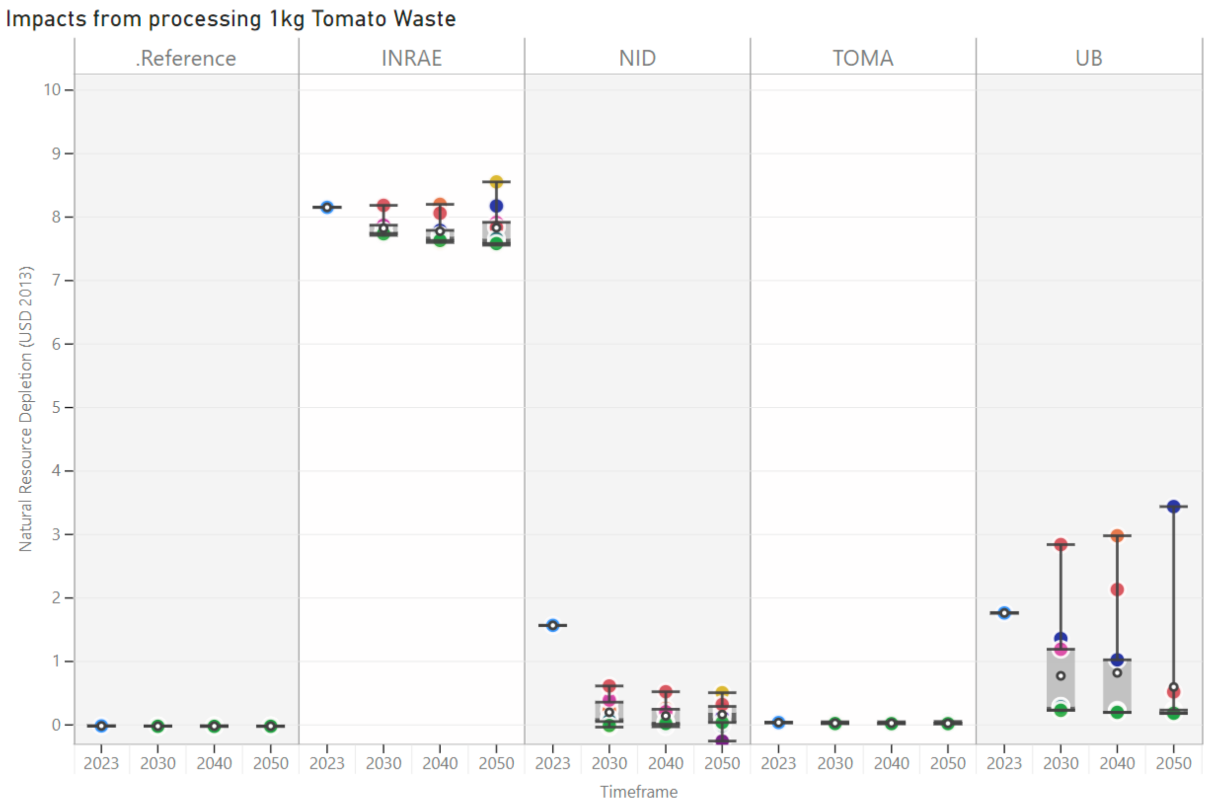

FIGURE 4 - CUMULATIVE NATURAL RESOURCE DEPLETION (RECIPE 2016 ENDPOINT (H)): THIS BOX-AND-WHISKER DIAGRAM SHOWS THE CUMULATIVE NATURAL RESOURCE DEPLETION VALUE OF THE PROCESSING PATHWAYS PROPOSED BY THE PROJECT PARTNERS INRAE, NID, TOMA, AND UNIBO (UB). '.REFERENCE' REFERS TO THE AVERAGE MARKET MIXTURE OF CURRENT TOMATO WASTE TREATMENT. EACH COLORED DOT REPRESENTS A THE IMPACT VALUES CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN USD 2013 PER 1 KG PROCESSED TOMATO WASTE.

A cumulative assessment of each of the value chains can be seen in Figure 3 and Figure 4. Each point of data is the result calculated using a separate SSP database, which have then been combined into box-and-whisker diagrams to show the range of impacts considering the possibility of futures. Looking solely at the GWP impacts of the value chains assessed, it would appear NID's process to produce PHA to substitute PET granulates provides the largest improvement. Of the remaining processes, each one produces GWP impacts greater than the current treatment processes used for tomato waste. In the case of TomaPaint's cutin production, the impacts are close enough to one another that no clear distinction can be made between which is more or less impactful.

Figure 4 illustrates the natural resource depletion impact category calculated via ReCiPe 2016 Endpoint (H). Of these, the reference and TomaPaint's processes perform consistently at almost a complete net zero. INRAE's pathway is again the most impactful in the category, followed by UNIBO.

Contribution Analysis

In this section we will explain each pathway's results in more detail, as well as identify impact hotspots to improve environmental efficiency.

INRAE

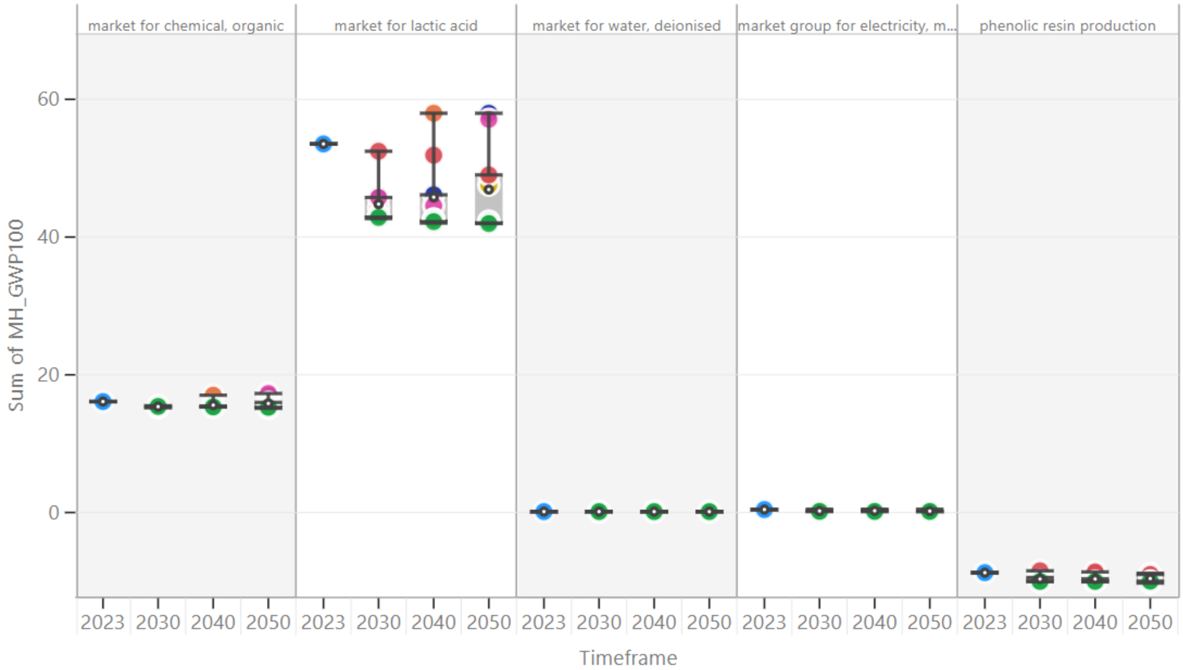

FIGURE 5 - INRAE GWP BY PROCESS (RECIPE MIDPOINT (H)): THIS BOX-AND-WHISKER DIAGRAM SHOWS THE IMPACTS OF EACH CONTRIBUTING PROCESS INCLUDED IN INRAE'S PROPOSED PROCESSING PATHWAY. EACH COLORED DOT REPRESENTS THE IMPACT VALUE CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN KG CO2E AND REFLECT THE IMPACT EACH PROCESS CONTRIBUTES TO THE TREATMENT OF 1 KG TOMATO WASTE. *CHOLINE CHLORIDE' WAS MODELED AS 'CHEMICALS, ORGANIC'. THE FINAL PRODUCT 'POLYPHENOLS' WAS MODELED AS 'PHENOLIC RESIN'.

INRAE's processes see some savings in the production of phenols (-8.87 kg CO2e/kg tomato in 2023) however, this is outweighed by the impacts resulting from organic chemicals and lactic acid, with values of 15.98 and 53.40 kg CO2e/kg tomato respectively as seen in Figure 5. This same effect can be seen in Figure 6 with Natural Resource Depletion.

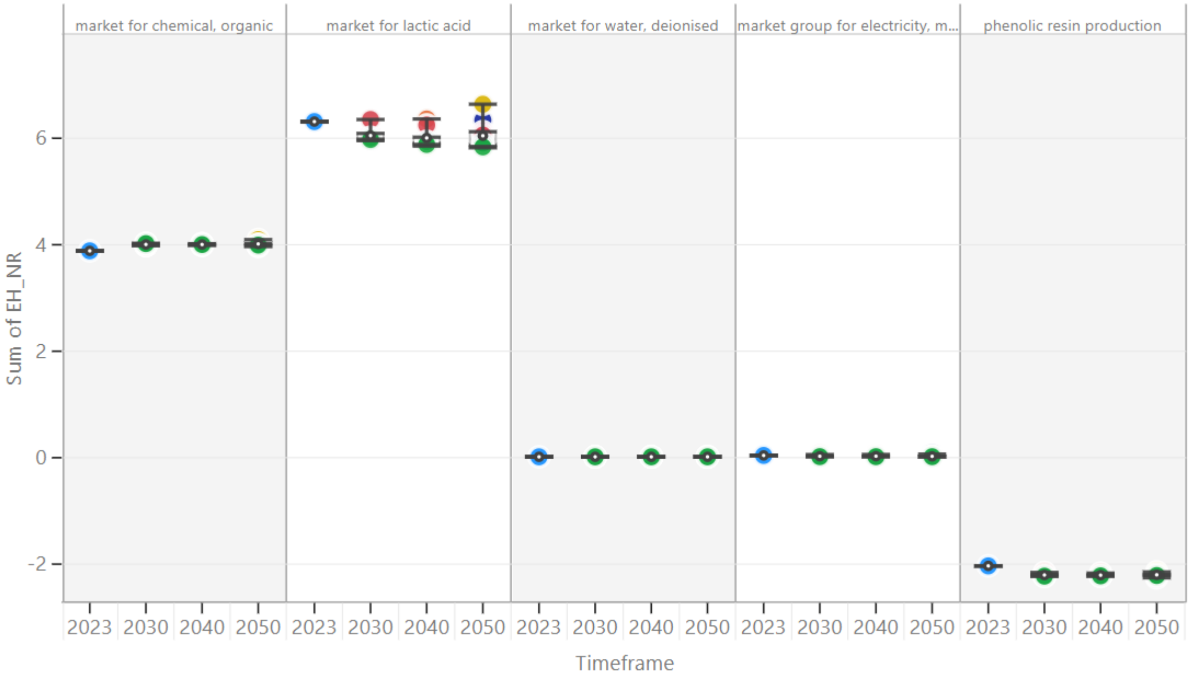

Figure 6 - INRAE Natural Resource Depletion by process (ReCiPe Endpoint (H)): This box-and-whisker diagram shows the impacts of each contributing process included in INRAE's proposed processing pathway. Each colored dot represents the impact value calculated for a separate SSP/RCP combination, with the small white dot indicating the mean of the results. Values are presented in USD 2013 and reflect the impact each process contributes to the treatment of 1 kg tomato waste. *Choline chloride' was modeled as 'chemicals, organic'. The final product 'polyphenols' was modeled as 'phenolic resin'.

These results suggest that efforts to reduce the consumption of chemicals, such as with efficient reuse of the DES, could prove beneficial to INRAE's processing pathway.

NID

As seen in Figure 7, NID's results indicate the largest GWP savings come from the production of hexane, as opposed to the substitution of plastic film. Further investigation revealed that this saving is due to savings coming from *avoiding* the production of *methylcyclohexane* upstream, *as well as avoiding* the production of *fraction 8* *from naphtha*. The remaining processes range in impact from ~0.83 to -0.11, however these are greatly overshadowed by the savings incurred through hexane's production processes.

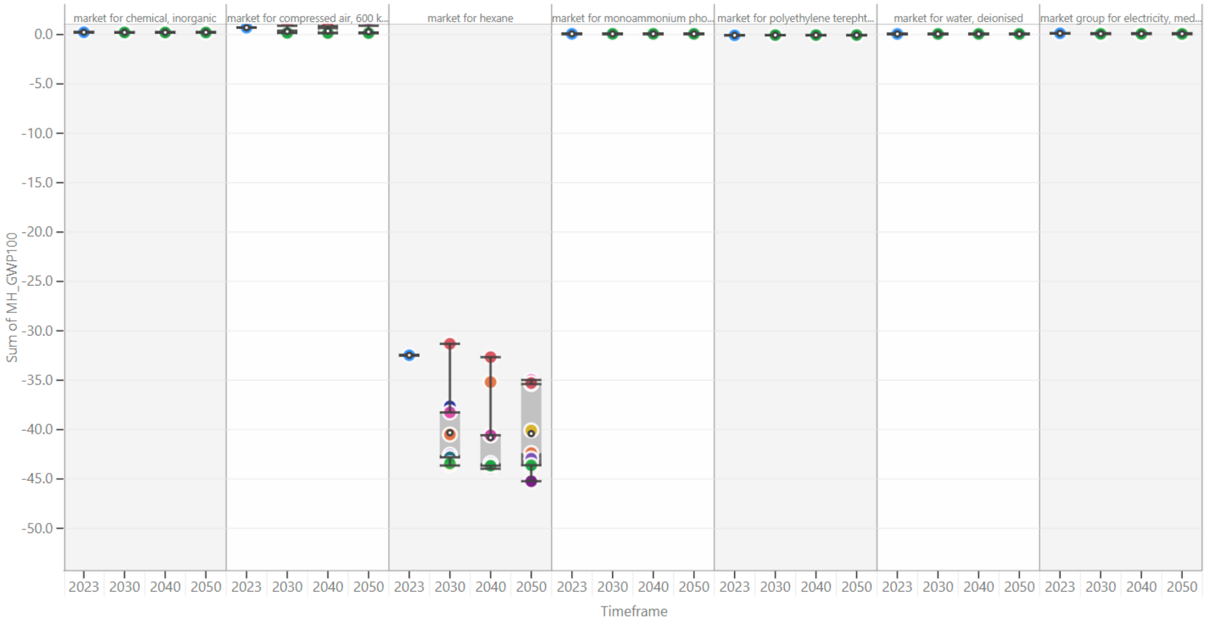

FIGURE 7 - NID GWP BY PROCESS (RECIPE MIDPOINT (H)): THIS BOX-AND-WHISKER DIAGRAM SHOWS THE IMPACTS OF EACH CONTRIBUTING PROCESS INCLUDED IN NID'S PROPOSED PROCESSING PATHWAY. EACH COLORED DOT REPRESENTS THE IMPACT VALUE CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN KG CO2E AND REFLECT THE IMPACT EACH PROCESS CONTRIBUTES TO THE TREATMENT OF 1 KG TOMATO WASTE. POTASSIUM AS KH2PO4 AND HYDROGEN PHOSPHATE AS K2HPO4 WERE MODELED AS "CHEMICAL, INORGANIC". AMMONIUM PHOSPHATE WAS MODELED AS "MONOAMMONIUM PHOSPHATE". THE FINAL PRODUCT OF PHA WAS ASSUMED TO SUBSTITUTE "POLYETHYLENE TEREPHTHALATE, GRANULATE, AMORPHOUS".

Conversely, Figure 8 indicates hexane is the largest contributor to NID's natural resource depletion. This is also due to the avoided production of methylcyclohexane. The significant outlier for hexane's impact in the year 2023 is likely to do with the specific *premise* configuration used in this assessment, where future markets are assumed to have perfect foresight and be "prepared" for the new demands in the market. See Sacchi, et. al [8] for more information on foresight.

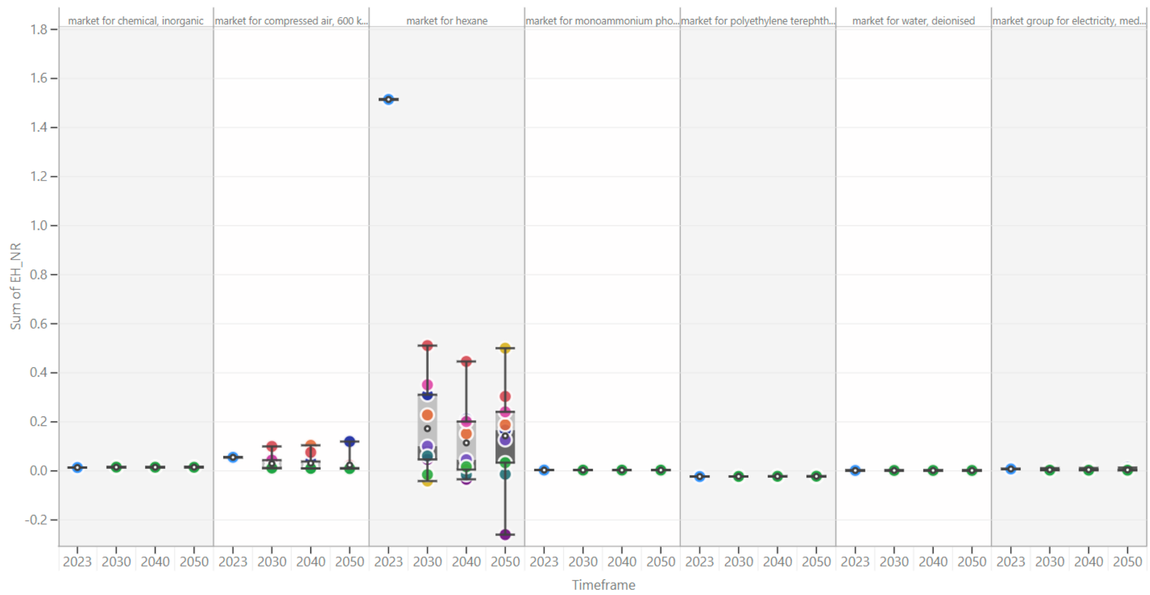

FIGURE 8 - NID NATURAL RESOURCE DEPLETION BY PROCESS (RECIPE ENDPOINT (H)) : THIS BOX-AND-WHISKER DIAGRAM SHOWS THE IMPACTS OF EACH CONTRIBUTING PROCESS INCLUDED IN NID'S PROPOSED PROCESSING PATHWAY. EACH COLORED DOT REPRESENTS THE IMPACT VALUE CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN USD 2013 AND REFLECT THE IMPACT EACH PROCESS CONTRIBUTES TO THE TREATMENT OF 1 KG TOMATO WASTE. POTASSIUM AS KH2PO4 AND HYDROGEN PHOSPHATE AS K2HPO4 WERE MODELED AS "CHEMICAL, INORGANIC". AMMONIUM PHOSPHATE WAS MODELED AS "MONOAMMONIUM PHOSPHATE". THE FINAL PRODUCT OF PHA WAS ASSUMED TO SUBSTITUTE "POLYETHYLENE TEREPHTHALATE, GRANULATE, AMORPHOUS".

UNIBO

UNIBO's high GWP impacts in Figure 9 and Figure 10 are the result of the use of an ISCO 2.8 kW oven in the pretreatment stage to dry the tomatoes. Furthermore, in the enzymatic digestion step, the liquid is held at 37 C for 2 hours, followed by a rapid increase to 100 C. This is a significantly higher energy demand on a per-kilo input basis than the other processes, and as such should be the first area addressed when optimizing this process.

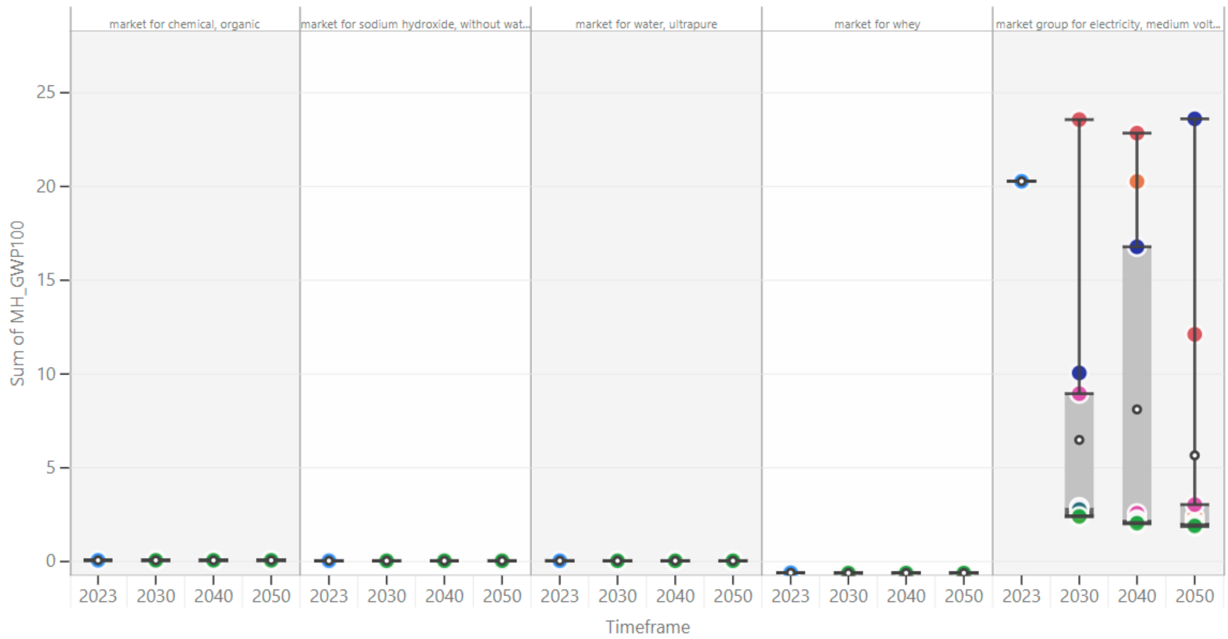

FIGURE 9 - UNIBO GWP BY PROCESS (RECIPE MIDPOINT (H)) : THIS BOX-AND-WHISKER DIAGRAM SHOWS THE IMPACTS OF EACH CONTRIBUTING PROCESS INCLUDED IN UNIBO'S PROPOSED PROCESSING PATHWAY. EACH COLORED DOT REPRESENTS THE IMPACT

VALUE CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN KG CO2E AND REFLECT THE IMPACT EACH PROCESS CONTRIBUTES TO THE TREATMENT OF 1 KG TOMATO WASTE. "TRYPSIN" WAS MODELED AS "CHEMICAL, ORGANIC". AS UNIBO SPECIFIED MILLIQ WATER, THEIR WATER CONSUMPTION WAS MODELED AS "WATER, ULTRAPURE". UNIBO'S OUTPUTS WERE MODELED AS "WHEY".

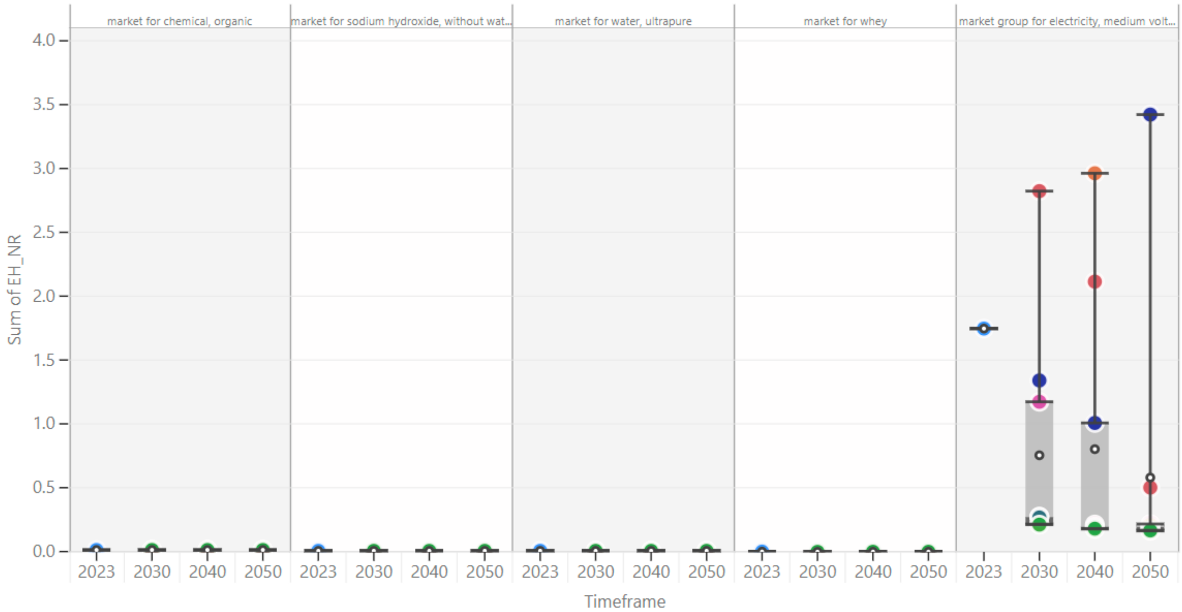

FIGURE 10 - UNIBO NATURAL RESOURCE DEPLETION BY PROCESS (RECIPE ENDPOINT (H)) : THIS BOX-AND-WHISKER DIAGRAM SHOWS THE IMPACTS OF EACH CONTRIBUTING PROCESS INCLUDED IN UNIBO'S PROPOSED PROCESSING PATHWAY. EACH COLORED DOT REPRESENTS THE IMPACT VALUE CALCULATED FOR A SEPARATE SSP/RCP COMBINATION, WITH THE SMALL WHITE DOT INDICATING THE MEAN OF THE RESULTS. VALUES ARE PRESENTED IN USD 2013 AND REFLECT THE IMPACT EACH PROCESS CONTRIBUTES TO THE TREATMENT OF 1 KG TOMATO WASTE. "TRYPSIN" WAS MODELED AS "CHEMICAL, ORGANIC". AS UNIBO SPECIFIED MILLIQ WATER, THEIR WATER CONSUMPTION WAS MODELED AS "WATER, ULTRAPURE". UNIBO'S OUTPUTS WERE MODELED AS "WHEY".

TomaPaint

By nature of being optimized for significantly larger quantities of throughput, TomaPaint's process is far more environmentally efficient per kilogram of tomato waste. Compressed air and electricity are TomaPaint's most- and second-most impactful processes respectively in both GWP and Natural Resource Depletion (Figure 11 and Figure 12), followed by wastewater treatment. This indicates the majority of TomaPaint's impacts arise from energy consumption, as opposed to the other pathways' impacts often resulting from the use of chemicals (such as lactic acid). TomaPaint has expressed the potential for the wastewater to reused in the system.

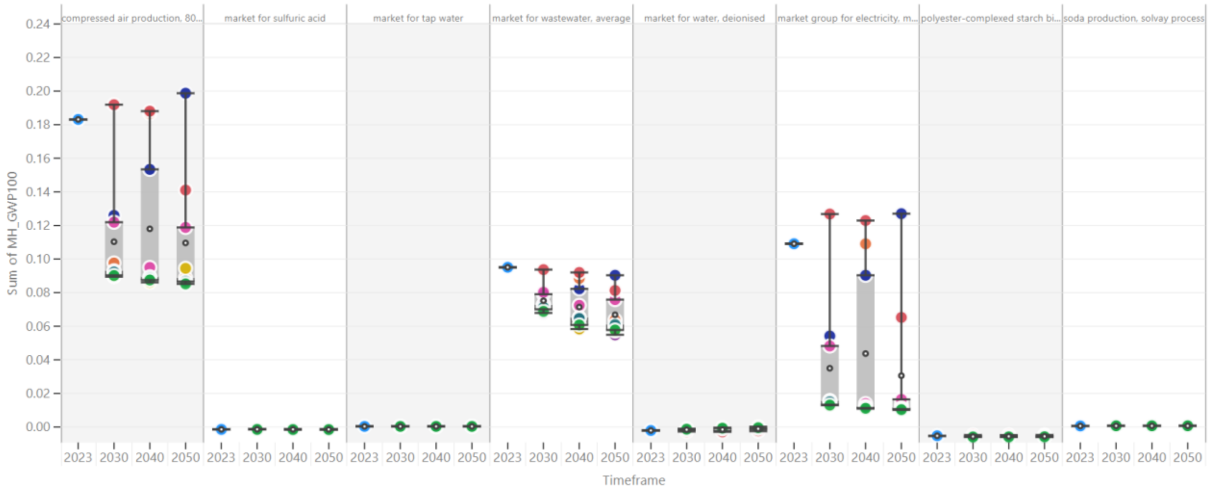

Figure 11 - TomaPaint GWP by process (ReCiPe Midpoint (H)): This box-and-whisker diagram shows the impacts of each contributing process included in TomaPaint's proposed processing pathway. Each colored dot represents the impact value calculated for a separate SSP/RCP combination, with the small white dot indicating the mean of the results. Values are presented in kg CO2e and reflect the impact each process contributes to the treatment of 1 kg tomato waste. Due to lacking inventory data, the final output product of cutin has been modeled as 'polyester-complexed starch biopolymer'.

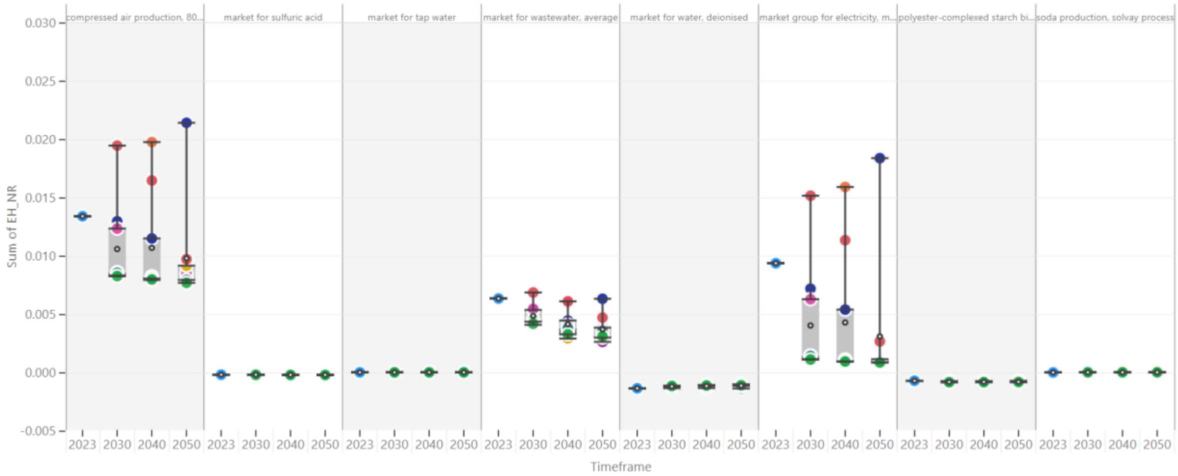

Figure 12 – TomaPaint Natural Resource Depletion by process (ReCiPe Endpoint (H)): This box-and-whisker diagram shows the impacts of each contributing process included in TomaPaint's proposed processing pathway. Each colored dot represents the impact value calculated for a separate SSP/RCP combination, with the small white dot indicating the mean of the results. Values are presented in USD 2013 and reflect the impact each process contributes to the treatment of 1 kg tomato waste. Due to lacking inventory data, the final output product of cutin has been modeled as 'polyester-complexed starch biopolymer'.

Reference

The estimations for current usage of tomato waste is mostly environmentally efficient with reference to GWP100 when used for animal feed (Figure 13). However, it would be naïve to assume savings could be maximized by using all tomato waste for feed, as one must consider all the impacts induced and avoided per substitution as opposed to only one. Figure 14 supports this analysis by indicating the production of biogas is the source of the most significant savings of natural resources.

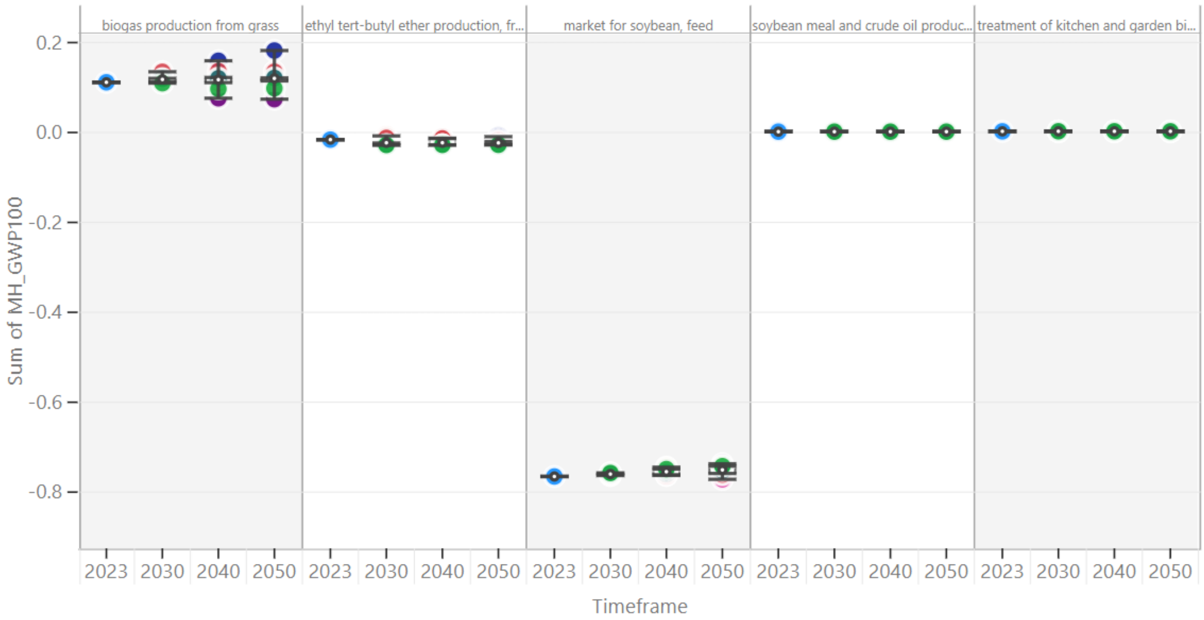

Figure 13 - Reference GWP by process (ReCiPe Midpoint (H)): This box-and-whisker diagram shows the impacts of the present-day processing pathways for tomato waste. Each colored dot represents the impact value calculated for a separate SSP/RCP combination, with the small white dot indicating the mean of the results. Values are presented in kg CO2e and reflect the impact each process contributes to the treatment of 1 kg tomato waste. To best estimate tomato processing emissions due to gaps in background databases, biogas production from tomato was modeled as 'biogas production, from grass'; bioethanol production was modeled as 'ethyl tert-butyl ether production'; lycopene production was modeled as 'soybean meal'; animal feed production was modeled as 'soybean feed'; and composting was modeled as 'treatment of biowaste, kitchen and garden waste'.

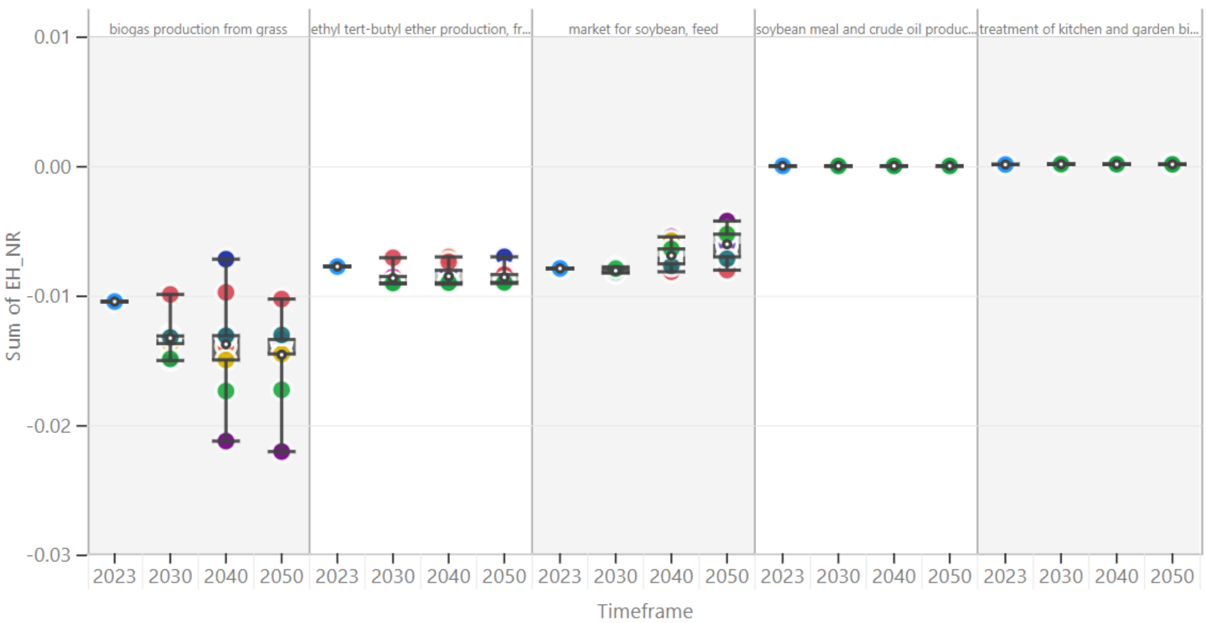

Figure 14 - Reference Natural Resource Depletion (USD 2013/kg tomato) by Process (ReCiPe Endpoint (H)): This box-and-whisker diagram shows the impacts of the present-day processing pathways for tomato waste. Each colored dot represents the impact value calculated for a separate SSP/RCP combination, with the small white dot indicating the mean of the results. Values are presented in USD 2013 and reflect the impact each process contributes to the treatment of 1 kg tomato waste. To best estimate tomato processing emissions due to gaps in background databases, biogas production from tomato was modeled as 'biogas production, from grass'; bioethanol

PRODUCTION WAS MODELED AS 'ETHYL TERT-BUTYL ETHER PRODUCTION'; LYCOPENE PRODUCTION WAS MODELED AS 'SOYBEAN MEAL'; ANIMAL FEED PRODUCTION WAS MODELED AS 'SOYBEAN FEED'; AND COMPOSTING WAS MODELED AS 'TREATMENT OF BIOWASTE, KITCHEN AND GARDEN WASTE'.

5. Discussion

Drying Energy

From the results, it appears that UNIBO's process is by far the most energy intensive due to heating requirements. However, this is not necessarily true for two reasons: first, that UNIBO and TomaPaint were the only two partners whose data specified a drying process, whereas the remaining partners were unclear if their input material was dried before they acquired it or if they required it to be dried at all; and second, UNIBO has indicated they can use dried seeds from TomaPaint, which dramatically lowers the energy demand of the UNIBO pathway.

Safety Indicators

Currently, the framework provides support for human health and safety in an indirect manner, by allowing the recipient of the data to assess the various impact category data related to human health, carcinogenic and non-carcinogenic toxicity, and more. In future revisions of this framework, we will add support for CAS number identification (where the background databases support it) in the ICSC Database[3] to flag specific compounds that can be found along the value chain of each process being assessed.

Prospective Databases with Paris Climate Agreement

While *premise* does support scenarios of each SSP where the specific climate goals are met, we recommend against considering impact values calculated using the Paris Climate Agreement (PkBudg) databases when making decisions. While the base versions of the SSPs are produced by calculating projected technological developments and market shares and using those results to reconstruct ecoinvent from the bottom up, the PkBudg databases are calculated in reverse. PkBudg databases are calculated by taking the estimated amount of climate change permissible to meet the specific goals (2.6 and 1.9) and then "forcing" the technologies available in the individual SSPs to make that specific goal possible from an emissions standpoint.

Data Gaps and Low-TRL Technologies

The results posited in this report are to be read with the understanding that they are early assessment results of low-TRL technologies and may not fully reflect the impacts of processes optimized for industrial scale.

From the literature review it is apparent that there is little recent data in the literature that is directly comparable to AgriLoop – different residue streams, outdated impact values, unclear methodologies, etc. Because of this, finding literature data to reasonably compare AgriLoop results to has been difficult and a number of substitutions have been made – such as all data relevant to the processing of tomato waste. This is especially relevant in the case of many of the final products – cutin and bioplastics data in particular are lacking in existing databases.

Combined with the existing gaps in the literature are the inherent gaps in low-TRL technologies. As most of the processes were at lab scale, heating and energy requirements were estimated, primarily using specific heat capacity calculations. In a pilot- or industrial-scale installation, it is assumed the energy costs will go down due to the use of technologies such as improved heat integration and overall better process insulation.

[3] https://chemicalsafety.ilo.org/dyn/icsc/showcard.home

6. Conclusion

With regards to the low-TRL of the assessed technologies and the data gaps present in the existing literature, the results presented in this report are to be seen as estimates and guidance. It should also be noted that these pathways are *not mutually exclusive*, and tests are being carried out to verify how these pathways can cascade. Figure 15 is an illustration showing potential crossovers between different tomato waste processing pathways (only concerning byproducts, *not* cascade), which from an environmental impact perspective would primarily avoid impacts by merging similar processes (e.g., TomaPaint's drying process being used for UNIBO).

Furthermore, several points were identified in each of the processes as potential hotspots of environmental impacts. The largest impacts were primarily induced through the production of chemicals (INRAE's lactic acid) and the need for heating (UNIBO's drying oven). Addressing these may increase the competitiveness of AgriLoop technologies versus the current processes used today. It should be noted that in the case of TomaPaint, the highest impacts arose from energy demand as opposed to chemical demand – indicating that there is potential for optimization for the lab-scale processes.

It must be noted however, that TomaPaint's optimized impacts were quite similar to the estimated impacts of present-day tomato waste processing pathways. The existing pathways include energy and food production that existing markets depend on. The impacts of AgriLoop processes were calculated under the assumption that a substitution would be made in the market, and as such the environmental impact savings would be equal to the difference between the impacts of AgriLoop production and those of the product being substituted. However, if an output is entering a growing market where supply cannot keep up with demand or if the product is in and of itself a new market, there is no substitution – and as such, no savings. In this case, there would be no savings associated with the final product of a given pathway, only the impacts incurred through requiring the existing market of lycopene and biogas to find suitable substitutions to meet their demands.

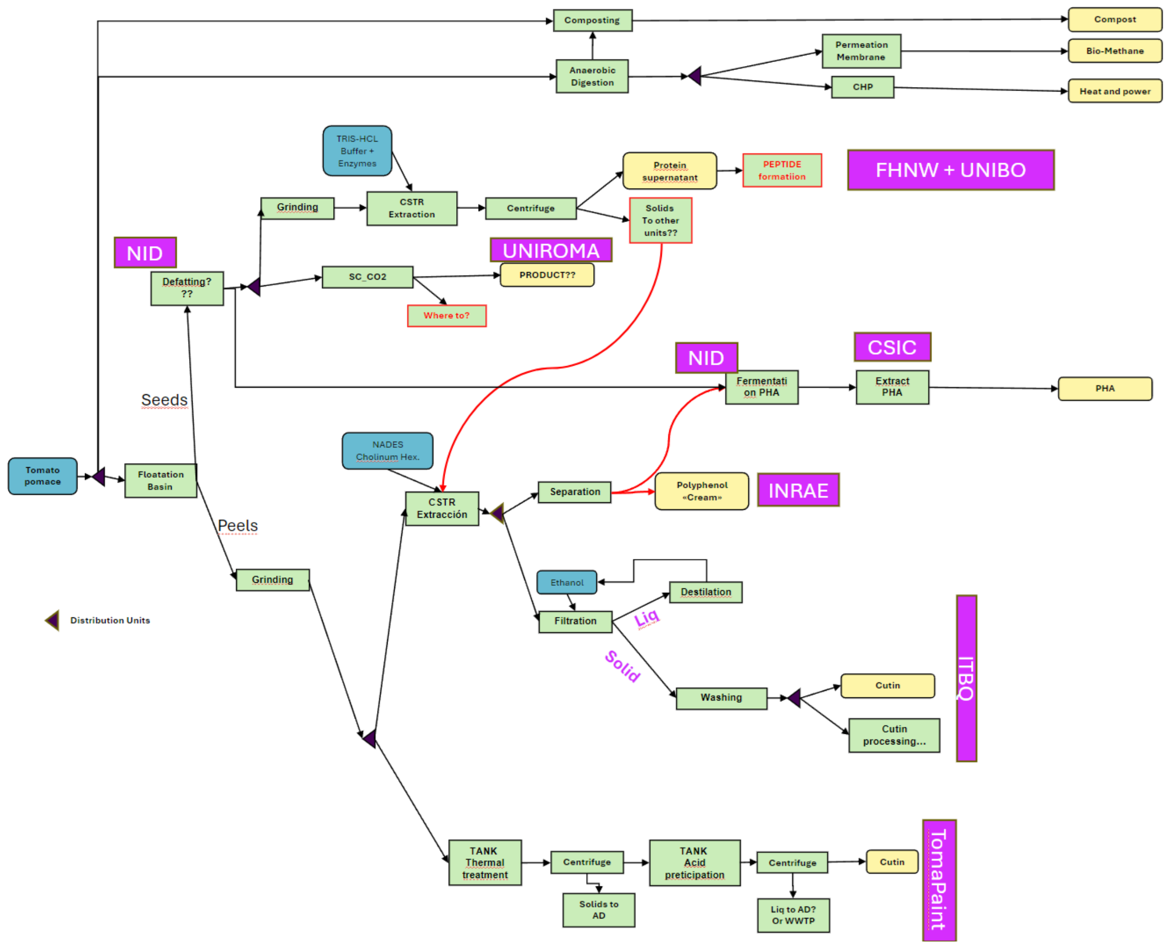

FIGURE 15 - DRAFT OF AGRILOOP SUPERSTRUCTURE BY LUCAS VAN DER HAUWAERT, USC – REPRODUCED WITH PERMISSION. THIS DIAGRAM REPRESENTS A HYPOTHETICAL MODEL OF HOW AGRILOOP PROCESSES CAN CASCADE INTO ONE ANOTHER WITH MULTIPLE

NON-MUTUALLY EXCLUSIVE PATHWAYS AND MULTIPLE OUTPUT PRODUCTS. BLUE BOXES INDICATE ADDITIONAL INPUTS. GREEN BOXES INDICATE PROCESSES. BLACK TRIANGLES INDICATE OUTPUT FLOW SPLITTING. PURLE BOXES INDICATE WHICH PARTNER IS DEVELOPING WHICH SERIES OF PROCESSES IN THE SUPERSTRUCTURE. YELLOW BOXES INDICATE FINAL PRODUCTS.

7. Data Management Plan follow-up

N°	Dataset name	Open Data	Closed Data	Means of dissemination	Maximum delay before access	Data set access
5	WP1.4_SDU_BK_1	Process specifications from partners, including compositions and yields.		Publication	Once published and at the latest 2 years after the end of the project	https://entrepot.recherche.data.gouv.fr/privateurl.xhtml?token=b870978b-cc2f-44fc-a989-6f427b95cee2
6	WP1.4_SDU_BK_2	Results of early assessment including processed results, raw data, input data, exported openLCA files, and configuration files.		Publication	Once published and at the latest 2 years after the end of the project	https://entrepot.recherche.data.gouv.fr/privateurl.xhtml?token=3bc369fc-5326-4125-9548-fdcc1a9323ea

This table above sums up the main information regarding the data produced for this deliverable, where is it stored and are the specific rules to respect concerning access, publication and FAIR principles.

N°	Dataset name	Owner	Name of the current contact	IPR issues	Use of third-party	Restrictions on data sharing (Y/N)
5	WP1.4_SDU_BK_1	SDU	Mias Sommer Schjønberg	Require data transfer contract with chinese partners for closed data	no	Yes, compliance with GDPR (see closed data)
6	WP1.4_SDU_BK_2	SDU	Mias Sommer Schjønberg			

This table above sums up the main information regarding potential Intellectual property protection or GDPR issues.

8. Annex I

TABLE 2 – LITERATURE REVIEW INTO LCA STUDIES PERFORMED ON THE PRODUCTION OF PHA BETWEEN THE YEARS OF 2019 AND 2024.

Citation	Background System Database	Boundary	Prospective	Agricultural Residues	Feedstock	FU
[14]	Ecoinvent, unclear	Cradle-to-Gate			Wastewater	1 kg VFA

[15]	Ecoinvent, consequential	Cradle-to-Gate	X	X	Corn stover, manure	1MJ bioethanol
[16]	Ecoinvent APOS				Bioplasticizers	
[4]	Ecoinvent 3.8 cut-off, Agrifootprint	Cradle-to-Gate, Gate-to-Grave		X	Fruit residues, wheat straw	Mass and volume of phbv pellets
[17]	Ecoinvent Cut-off	Cradle-to-Gate			Corn steep liquor, glucose	1t PHB
[18]	Ecoinvent 3.6	Cradle-to-Grave			CH4, NH4, H2SO4	1kg PHB
[19]	Unspecified	Cradle-to-Gate			Sewage sludge	
[20]	Ecoinvent 3.9.1	Cradle-to-Gate		X	sugarcane, corn stover	1 kg aPHA
[21]	Ecoinvent 3.2	Gate-to-Grave			From supplier	1 t 80/20 PLA/PHBV blend
[22]	GaBi	Gate-to-Gate			Brewers' spent grain	kg PHB
[23]	Ecoinvent.3.9	Cradle-to-Grave		X	Semolina, durum wheat pasta	1 resuable plate, 1 freezer bag, 1 biscuit bag
[5]	Ecoinvent 3.7.1	Cradle-to-Gate	X	X	Fruit waste, Organic fraction of Municipal Solid Waste	t PHA/y
[6]	Ecoinvent 3.8	Cradle-to-Gate			Wastewater, BG-11	1 kg PHB
[24]	Ecoinvent 3.7.1, Cut-off	Cradle-to-Gate			Wastewater	1 kg PHA
[25]	Ecoinvent 3.8, cutoff	Cradle-to-Gate			Organic fraction of Municipal Solid Waste	1 t PHA
[26]	TRACI	Gate-to-Gate			Soap production, 3 biodiesel scenarios	7500 t PHB
[27]	N/A	N/A			PHA	1 kg PHA
[28]	Ecoinvent 3.8	Cradle-to-Grave			PHBV	150g packaged falafel
[29]	Ecoinvent	Cradle-to-Gate			PHB w/ cellulose nanocrystrals	100g composite
[30]	Ecoinvent Consequential	Cradle-to-Gate			OFMSW	145.000 t/y OFMSW
[7]	TRACI	Cradle-to-Gate		X	Sugarcane	1kg PHB
[31]	Ecoinvent 3.8 + GaBi Bioplastics 2019	Cradle-to-Grave			Unclear	Unclear
[32]	Ecoinvent 3.7, Cut-off	Cradle-to-Grave			glycerol	1kg PHB
[33]	Unclear	Unclear			Unclear	One face shield
[34]	Ecoinvent 3.6, Consequential	Cradle-to-Grave		½	Molasses	0.06384m2 ofPHA-based plastic film

[35]	Ecoinvent 3.3, likely cutoff	Gate-to-Gate		X	Molasses, canning industry waste, food industry byproducts, etc.	1kg high grade PHA powder, 1 kg low grade PHA powder
[36]	Allocation Def, Ecoinvent 3.4	Cradle-to-Gate			DMC/ethanol, chloroform/hexane	1g PHB
[37]	Ecoinvent, Cut-off	Cradle-to-Gate		X	oil palm empty fruit branches	9000t PHA
[38]	GaBi	Cradle-to-Gate		X	Sunflower oil + meal, crude glycerol (from biodiesel production)	1kg PHB
[39]	EFSD, ELCD, Ecoinvent 2.2, Plastics Europe,	Cradle-to-Grave		X	Sugar beet, sugarcane, corn	Film required for 1kg produce, 0,079m2 multilayer PHA film |ref flow 1kg beef
[40]	Ecoinvent i3.1 simapro	Cradle-to-Gate			polyethylene-derived fatty acid mixture	1 kg post-consumer PE
[41]	Ecoinvent 3.4, cutoff	Cradle-to-Grave		X	market PHBV	1x standard tray
[2]	TRACI, considers substitution in some parts of system	Cradle-to-Gate		X	cow manure, WW	454 kg COD
[42]	Ei3.0, manual substitution considered	Cradle-to-Gate	X		cheese whey	1t cheese whey
[43]	GaBi Professional, Ecoinvent 2 cutoff	Cradle-to-Grave			Anaerobically digested sewage sludge	1kg biopolymer
[1]	Ecoinvent 3.4, Consequential	Gate-to-Gate		X	Chicken/cow/pig manure | grass, corn silage | wheat, soybean straw | corn stover | vine shoots | grape pomace | sugar beet pulp | grain	1 ton feedstock
[3]	Ecoinvent 3.3 cut-off	Gate-to-Gate			Mussel cooking wastewater	85m^3/day
[44]	Ecoinvent 3.1	Cradle-to-Gate		X	Rapeseed oil byproducts, used oil, biodiesel byproduct (glycerol)	1kg raw biopolymer
[45]	Ecoinvent 3, Agri-Footprint, EXIOBASE	Cradle-to-Gate		X	potato pulp	1kg biocomposite
[46]	Ecoinvent 3.4, considers marginals	Gate-to-Gate	X	X	liquid cow manure, solid cow manure, wine pomace, wine marc	1t feedstock
[47]	Ecoinvent 3.0	Cradle-to-Gate		X	sugarcane lignocellulosic feedstock: bagasse and "tops and trash"	65t/hour feedstock
[48]	Ecoinvent, unspecified; Gabi	Cradle-to-Gate		X	Soybean oil	1kg PHB

	Professional; Plastics Europe					
[49]	Ecoinvent 3.3, likely cutoff	Gate-to-Grave			MSW	442 tons MSW disposed of

9. Annex II

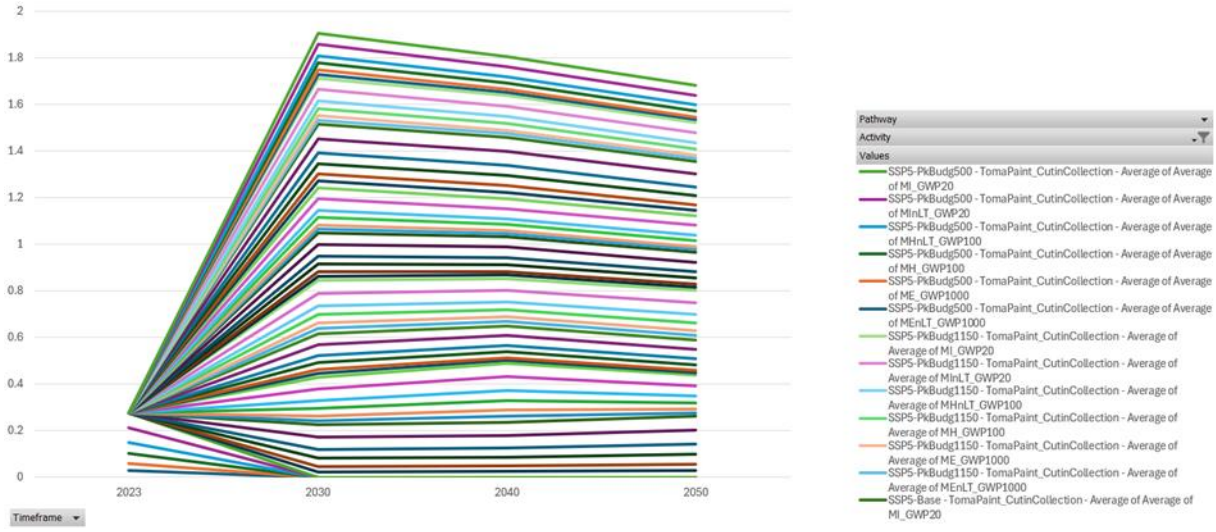

FIGURE 16 – THE CO2E IMPACTS OF TOMAPAINT'S CUTIN COLLECTION PROCESS. DISPLAYED ARE CO2E IMPACTS CALCULATED USING EVERY RECIPE 2016 MIDPOINT GWP INDICATOR, INCLUDING EGALITARIAN, HIERARCHIST, AND INDIVIDUALIST CULTURAL PERSPECTIVES; AS WELL AS THE INCLUSION OR EXCLUSION OF LONG-TERM EMISSIONS ('NO LT'). THESE IMPACTS WERE CALCULATED FOR 2023, 2030, 2040, AND 2050; FOR SSPS 1, 2, AND 5 WITH BASE, PKBUDG1150, AND PKBUDG500 RCPS. THE SIX DISPLAYED IMPACT CATEGORIES IN THIS FIGURE ARE OUT OF A TOTAL OF 256 IMPACT CATEGORIES CALCULATED. ALL CALCULATED RESULTS FOR ALL PROCESSES AND INDICATORS CAN BE FOUND IN THE SUPPLEMENTARY DATA.

10. References

1. Vega, G.C., et al., *Assessing new biotechnologies by combining TEA and TM-LCA for an efficient use of biomass resources.* Sustainability (Switzerland), 2020. **12**(9).
2. Bryant, C. and E.R. Coats, *Integrating dairy manure for enhanced resource recovery at a WRRF: Environmental life cycle and pilot-scale analyses.* Water Environment Research, 2021. **93**(10): p. 2034-2050.
3. Roibás-Rozas, A., A. Mosquera-Corral, and A. Hospido, *Environmental assessment of complex wastewater valorisation by polyhydroxyalkanoates production.* Science of the Total Environment, 2020. **744**.
4. Nhu, T.T., et al., *Environmental sustainability assessment of biodegradable bio-based poly(3-hydroxybutyrate-co-3-hydroxyvalerate) from agro-residues: Production and end-of-life scenarios.* Journal of Environmental Management, 2024. **356**.
5. Saavedra del Oso, M., et al., *Prospective LCA to provide environmental guidance for developing waste-to-PHA biorefineries.* Journal of Cleaner Production, 2023. **383**.
6. Rueda, E., et al., *Life cycle assessment and economic analysis of bioplastics production from cyanobacteria.* Sustainable Materials and Technologies, 2023. **35**: p. 11.
7. Kane, S., et al., *Reducing the environmental impacts of plastics while increasing strength: Biochar fillers in biodegradable, recycled, and fossil-fuel derived plastics.* Composites Part C: Open Access, 2022. **8**: p. 9.
8. Sacchi, R., et al., *PRospective EnvironMental Impact asSEment (<i>premise</i>): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models.* RENEWABLE & SUSTAINABLE ENERGY REVIEWS, 2022. **160**.
9. *openLCA*. [cited 2024; Available from: https://www.openlca.org/.
10. Mutel, C., *Brightway: An open source framework for Life Cycle Assessment.* The Journal of Open Source Software, 2017. **2**(12): p. 236.
11. Wernet, G., et al., *The ecoinvent database version 3 (part I): overview and methodology.* The International Journal of Life Cycle Assessment, 2016. **21**(9): p. 1218-1230.
12. O'Neill, B.C., et al., *A new scenario framework for climate change research: the concept of shared socioeconomic pathways.* Climatic Change, 2014. **122**(3): p. 387-400.
13. Baumstark, L., et al., *REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits.* Geosci. Model Dev., 2021. **14**(10): p. 6571-6603.
14. Gracia, J., I. Cabeza, and P. Acevedo, *Life cycle analysis for the production of volatile fatty acids from wastewater treatment plant sludge.* Cogent Engineering, 2024. **11**(1): p. 13.
15. Wang, Y., et al., *Co-Processing Agricultural Residues and Wet Organic Waste Can Produce Lower-Cost Carbon-Negative Fuels and Bioplastics.* Environmental Science and Technology, 2023. **57**(7): p. 2958-2969.
16. Ruini, C., et al., *Innovative Bioplasticizers from Residual Cynara cardunculus L. Biomass-Derived Levulinic Acid and Their Environmental Impact Assessment by LCA Methodology.* ACS Sustainable Chemistry and Engineering, 2023. **11**(32): p. 12014-12026.
17. Rawat, S. and S. Goswami, *Synergistic approach for enhanced production of polyhydroxybutyrate by Bacillus pseudomycoides SAS-B1: Effective utilization of glycerol and acrylic acid through fed-batch fermentation and its environmental impact assessment.* International Journal of Biological Macromolecules, 2024. **258**.
18. Park, D., H. Lee, and W. Won, *Unveiling the environmental gains of biodegradable plastics in the waste treatment phase: A cradle-to-crave life cycle assessment.* Chemical Engineering Journal, 2024. **487**: p. 13.
19. Mannina, G. and A. Mineo, *A comprehensive comparison between two strategies to produce polyhydroxyalkanoates from domestic sewage sludge.* Journal of Cleaner Production, 2024. **468**.
20. Lee, S., et al., *Life Cycle Assessment of aPHA Production.* ACS Sustainable Chemistry and Engineering, 2024. **12**(1): p. 72-84.
21. dos Anjos, E.G.R., et al., *Biodegradation Behavior and Life Cycle Assessment of PLA/PHBV/Carbonaceous Materials Hybrid Nanocomposites for Antimicrobial Multifunctional Packaging.* Journal of Polymers and the Environment, 2024.
22. Argeiti, C., et al., *Biorefinery electrification of brewers' spent grains using plasma bubbles for sustainable production of poly(3-hydroxybutyrate).* Chemical Engineering Journal, 2024. **496**: p. 15.

23. Saavedra del Oso, M., et al., *Comparative life cycle analysis of PHA-based consumer items for daily use.* Resources, Conservation and Recycling, 2023. **199**.
24. Roibás-Rozas, A., et al., *A circular economy strategy for valorizing industrial saline wastewaters: Techno-economics and environmental impacts.* Chemical Engineering Journal, 2023. **472**.
25. Martin-Gamboa, M., et al., *Environmental life cycle assessment of polyhydroxyalkanoates production by purple phototrophic bacteria mixed cultures.* Journal of Cleaner Production, 2023. **428**: p. 12.
26. Kolonnage, T.N. and I.M.L. Chew, *Environmental and cost analysis for polyhydroxyalkanoate production from glycerol byproduct: A case study from integrated soap and biodiesel plants.* Cleaner Environmental Systems, 2023. **9**: p. 15.
27. Corella-Puertas, E., et al., *MarILCA characterization factors for microplastic impacts in life cycle assessment: Physical effects on biota from emissions to aquatic environments.* Journal of Cleaner Production, 2023. **418**: p. 12.
28. Boone, L., et al., *Environmental performance of plastic food packaging: Life cycle assessment extended with costs on marine ecosystem services.* Science of the Total Environment, 2023. **894**.
29. Ansari Movahed, D., et al., *Life cycle assessment and mechanical properties of nanocomposites based on cellulose nanocrystals.* Polymer Engineering and Science, 2023. **63**(6): p. 1752-1760.
30. Rossi, E., et al., *Environmental impacts of dry anaerobic biorefineries in a Life Cycle Assessment (LCA) approach.* Journal of Cleaner Production, 2022. **371**: p. 14.
31. Ibarretxe, J., et al., *Sustainable PHBH–Alumina Nanowire Nanocomposites: Properties and Life Cycle Assessment.* Polymers, 2022. **14**(22).
32. Cañado, N., et al., *3D printing to enable the reuse of marine plastic waste with reduced environmental impacts.* Journal of Industrial Ecology, 2022. **26**(6): p. 2092-2107.
33. Zgodavová, K., et al., *3D Printing Optimization for Environmental Sustainability: Experimenting with Materials of Protective Face Shield Frames.* Materials, 2021. **14**(21): p. 19.
34. Vea, E.B., et al., *Inclusion of multiple climate tipping as a new impact category in life cycle assessment of polyhydroxyalkanoate (PHA)-based plastics.* Science of the Total Environment, 2021. **788**.
35. Saavedra del Oso, M., M. Mauricio-Iglesias, and A. Hospido, *Evaluation and optimization of the environmental performance of PHA downstream processing.* Chemical Engineering Journal, 2021. **412**.
36. Mongili, B., et al., *Novel insights in dimethyl carbonate-based extraction of polyhydroxybutyrate (PHB).* Biotechnology for Biofuels, 2021. **14**(1).
37. Loh, Y.Z. and I.M.L. Chew, *Mitigating plastic pollution through better process design: an opportunity from biomass to bioplastic.* Biomass Conversion and Biorefinery, 2021: p. 22.
38. Kachrimanidou, V., et al., *Techno-economic evaluation and life-cycle assessment of poly(3-hydroxybutyrate) production within a biorefinery concept using sunflower-based biodiesel industry by-products.* Bioresource Technology, 2021. **326**.
39. Hutchings, N., et al., *Comparative life cycle analysis of a biodegradable multilayer film and a conventional multilayer film for fresh meat modified atmosphere packaging – and effectively accounting for shelf-life.* Journal of Cleaner Production, 2021. **327**.
40. Guzik, M.W., et al., *Robust process for high yield conversion of non-degradable polyethylene to a biodegradable plastic using a chemo-biotechnological approach.* Waste Management, 2021. **135**: p. 60-69.
41. David, G., et al., *Using life cycle assessment to quantify the environmental benefit of upcycling vine shoots as fillers in biocomposite packaging materials.* International Journal of Life Cycle Assessment, 2021. **26**(4): p. 738-752.
42. Asunis, F., et al., *Environmental life cycle assessment of polyhydroxyalkanoates production from cheese whey.* Waste Management, 2021. **132**: p. 31-43.
43. Vogli, L., et al., *Life cycle assessment and energy balance of a novel polyhydroxyalkanoates production process with mixed microbial cultures fed on pyrolytic products of wastewater treatment sludge.* Energies, 2020. **13**(11).
44. Nitkiewicz, T., et al., *How sustainable are biopolymers? Findings from a life cycle assessment of polyhydroxyalkanoate production from rapeseed-oil derivatives.* Science of the Total Environment, 2020. **749**.
45. Chen, W., et al., *Hybrid life cycle assessment of potato pulp valorisation in biocomposite production.* Journal of Cleaner Production, 2020. **269**.
46. Vega, G.C., et al., *Maximizing environmental impact savings potential through innovative biorefinery alternatives: An application of the TM-LCA framework for regional scale impact assessment.* Sustainability (Switzerland), 2019. **11**(14).

47. Nieder-Heitmann, M., K.F. Haigh, and J.F. Görgens, *Life cycle assessment and multi-criteria analysis of sugarcane biorefinery scenarios: Finding a sustainable solution for the South African sugar industry.* Journal of Cleaner Production, 2019. **239**: p. 17.
48. Kookos, I.K., A. Koutinas, and A. Vlysidis, *Life cycle assessment of bioprocessing schemes for poly(3-hydroxybutyrate) production using soybean oil and sucrose as carbon sources.* Resources, Conservation and Recycling, 2019. **141**: p. 317-328.
49. Fernández-Braña, Á., G. Feijoo-Costa, and C. Dias-Ferreira, *Looking beyond the banning of lightweight bags: analysing the role of plastic (and fuel) impacts in waste collection at a Portuguese city.* Environmental Science and Pollution Research, 2019. **26**(35): p. 35629-35647.