NoAW project

Innovative approaches to turn agricultural waste into ecological and economic assets

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CO Confidential, only for members of the consortium (including the Commission Services)	

2. Summary

Background	In the NoAW project a large number of technologies are developed to transform agricultural residues into novel and eco-friendly products. The focus is to study how residues from grape cultivation, wine production, animal husbandry and cereal cultivation function as raw materials for production of bio-active molecules, bioenergy, chemicals, building-blocks and materials. This includes both technical, economic and environmental aspects. WP2, of which this deliverable is part, seeks to integrate these aspects under novel assessments methods. Based on the environmental assessments, new decision support has been developed.
Objectives	The main objective of D2.5 is to apply environmental assessment methods on selected NoAW technologies, in order to facilitate decision making.
Methods	The methods used in this deliverable is Life Cycle Assessment (LCA) and Multi Criteria Decision Analysis (MCDA). Also Techno-economic assessment (TEA) was included even though it is not in focus of the deliverable. MCDA was applied to create decision support based on results from LCA and TEA.
Results & implications	Based on a technical feasibility study, case studies for environmental assessments were chosen. A selection of case studies is presented in this deliverable. It was shown that trays made of biocomposite materials including vine shoot fillers had a better environmental performance than trays made from pure polymers. LCA and TEA were carried out on different options to extract polyphenols from grape pomace. MCDA was applied to create decision support based on the results generated from LCA and TEA.

3. Introduction

The H2020 project NoAW has as its goal to contribute to a ‘near zero-waste society’ by promoting a circular economy in which agricultural waste, by- and co-products are turned into eco-efficient bio-based products with direct benefits for the environment, economy and society. The focus is to study how residues from grape cultivation, wine production, animal husbandry and cereal cultivation function as raw materials for production of bio-active molecules, bioenergy, chemicals, building-blocks and materials. This includes both technical, economic and environmental aspects. WP2 seeks to integrate the environmental aspects under novel assessments methods. As such, WP2, which is in charge of “assessment and strategic management of agro-waste in circular, territorial and seasonal perspectives through hybridized approaches and innovative decision support” has developed “innovative and robust approaches and tools adapted to the assessment and determination of optimal agro-waste management strategies at appropriate (regional) scale and complexity levels, with consistent guidance.” The main objective of D2.5 is to apply the above-named methods developed within the WP to selected NoAW technologies, in order to facilitate decision making.

The work presented in this deliverable is focused on Life Cycle Assessment (LCA) and Multi Criteria Decision Analysis (MCDA). WP2 includes other methods that address both environmental issues such as Multi Criteria Evaluation (MCE) in Strategic Environmental Assessment (SEA) and stakeholders´ preferences that can be applied in decision support. The application of these methodologies were described in detail in NoAW deliverables D2.3 and D2.4.

Knowledge about environmental impact is very important to make well informed decisions. It has been shown that, when policy makers, corporations, or any other actor is faced with the need to choose between alternative solutions to a given problem, there is often a multitude of issues to be taken into account. And, the decision-making context surrounding such a choice can be handled in many ways, from community-based decision making to round table discussions or even executive fiat. However, without a tool for handling fundamentally conflicting information, the results of decision making through discussion can vary wildly and may depend on happenstance and or subjective factors. Multiple Criteria Decision Analysis (MCDA) has previously been applied to aid in alleviating these problems by introducing a transparent and repeatable form of decision support (Köksalan et al., 2011). On the other hand, before making a final decision it is necessary to have economic and environmental information of the selected technologies, which can be then used for applying MCDA as described in ((Sohn et al., 2019)). For these goals, techno-economic assessment can be applied for process flow design optimization at an early stage in combination with life-cycle assessment (Croxatto Vega et al., 2019), which is capable of providing holistic information on the potential environmental impacts of a choice.

The following report includes a technical feasibility study that describes the process of selecting case studies and excerpts from three different studies performed within the framework of NoAW WP2. These three studies are, “Life cycle assessment of bio-composite packaging materials introducing vine shoots as fillers” (David et al., 2019) “Lessons from combining techno-economic and life-cycle assessment - a case study of polyphenol extraction from waste resources” (Croxatto Vega et al., 2019) and “Incorporating Relative Importance: selecting a polyphenol production method for agro-waste treatment in an environmental and economic multi-criteria decision making context” (Sohn et al., 2019).

4. Technical Feasibility Evaluation of NoAW Technologies and products

The aim of the technical feasibility study was to get an overview of the technologies that were developed in the project, how they relate to each other and how they can or cannot be combined. Based on this knowledge, case studies could be selected and, assessments with a goal and scope relevant for each case could be performed. The process for choosing case studies is presented below in section 4.4.

The technological pathways developed by the NoAW consortium are of pilot, industrial, and experimental scale. As such, the large-scale technologies (pilot and industrial scale) are designed to treat a wide range of organic residues including, but not limited to, animal slurries, residues rich in lignocellulose, energy crops and wine pomaces. The lab scale technologies specialize in extracting interesting biomolecules in low volumes for specialty uses. The large-scale technologies include several biogas configurations with some variations in the products produced.

The large-scale technologies represent Anaerobic Digestion (AD) platforms, which have the possibility to serve as a base for biorefinery concepts with cascading products, if they are combined with some of the lab scale technologies (in an up-scaled version) to produce several products in one place. The overview allows us to imagine new biorefinery concepts and support when deciding which will be assessed with the methods developed in WP2.

4.1 AD Platforms

- Innoven's process is an AD-based process with two fermentation steps (2StepPHA) producing biogas and Polyhydroxyalkanoates (PHAs) at a pilot scale near Verona, Italy. PHAs are flexible polyesters, ranging from brittle thermoplastics to gummy elastomers, which are produced by bacteria. The novelty of PHAs lies in that they do not accumulate in the marine environment (Dietrich et al., 2017), furthermore, this polymer can be combined with other treated agricultural feedstock as, for example vine shoots, to produce biocomposites. This work was carried out at INRA in Montpellier. Also, PHAs are biodegradable by composting according to ASTM[1] standards (Dietrich et al., 2017).. A biogas upgrade unit is also in the plans for this set-up. The pilot upgrade unit is being developed by the group at La Sapienza and will upgrade the CO_2 in the biogas to CH_4, via biomass that consumes VFAs. The microbial electrolysis cell (MEC) will be moved to the pilot site and consumes a portion of the VFA produced in this set up.

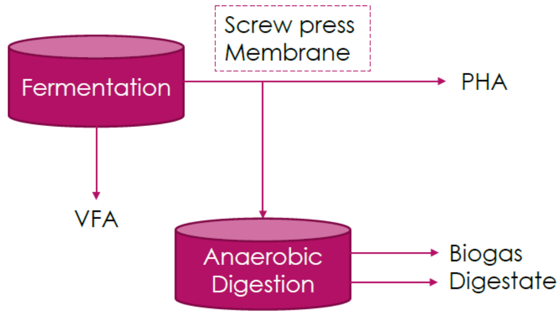

Figure 1. 2-stage thermophilic anaerobic digestion with PHA production

[1] American Section of the International Association for Testing Materials

Similarly, a process being developed in a pilot plant by LBE-INRA Narbonne is almost identical to Innoven's process, except there is no production of PHA. The objective of this technology is to increase the production of H_2 (around 10% of total biogas by volume) in the first fermentation step so that the overall energetic content of the biogas is higher and the total CO_2 production is lowered. The production of hydrogen gas is also present in the Innoven pilot scale; however, their focus is to maximize VFA production for further PHA selection.

- The process developed by BioVantage is a treatment designed to target the lignocellulosic fraction of agricultural residues so as to break down the lignin and increase the methane yield, thus the name AD Booster. This is a proven technology that is already in operation at industrial scale in biogas plants around Denmark, and it relies on animal slurries as carrier for the lignocellulosic material.

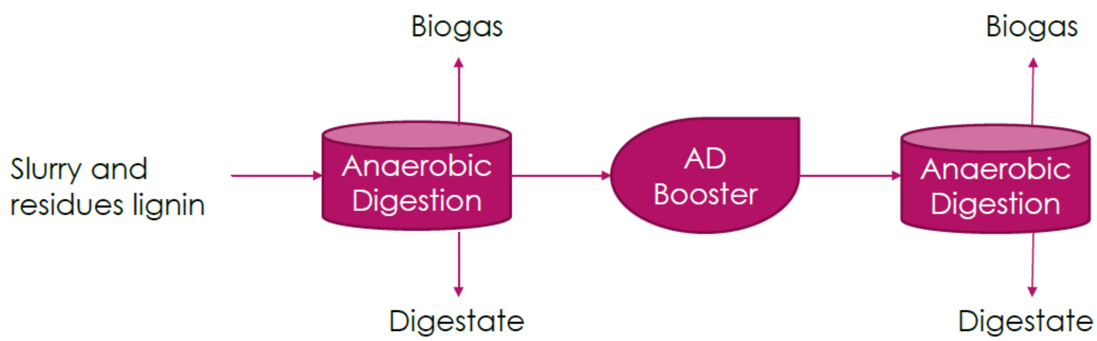

Figure 2. AD-Booster treatment for the lignin fraction of agricultural residues

- NTUA is developing a pilot scale, mesophilic bioreactor, that processes wheat straw. There is no schematic diagram for this process. Water and wheat straw that has previously been shredded are fed to the AD reactor, afterwards the straw digestate, rich in lignocellulose material still, is treated enzymatically to retrieve ethanol.

4.2. Experimental scale technologies

The following is a list of the emerging technologies at a lab scale. The numbers assigned to each type of processing are used in the discussion of compatibility below.

1. Extraction and depolymerization of condensed tannins (CT) from grape stalks and vine shoots (INRA) to make new polymeric structures
2. Photo-fermentation of PHA using mixed culture of photosynthetic organisms (IBET)
3. Gas-phase esterification to treat lignocellulose and use as filler in biocomposites (UM-INRA)

4. Enzymatic, chemical, and pressurized liquid extraction of polyphenols, with supercritical CO_2 from wine pomaces (UNIBO and RISE).
5. Succinic acid fermentation from vegetable and fruit waste (City U) (many applications, see Figure 3). This can be used in combination with the depolymerized tannins to make epoxy resins. The technology applies to residues that lead to glucose-rich syrups or carbon sources such as glycerol (also a by-product of industry).

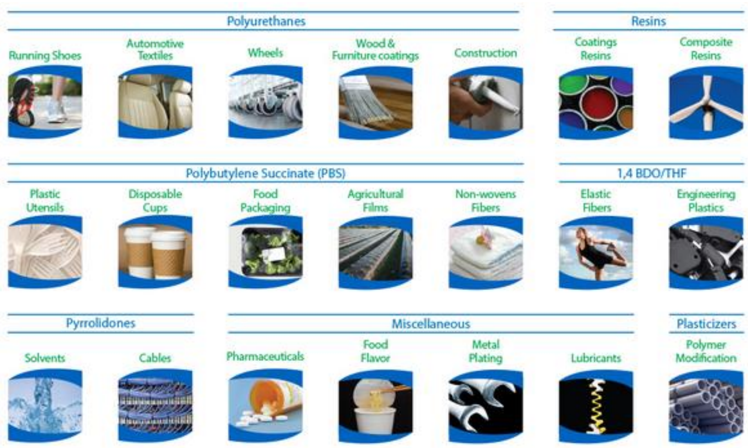

Figure 3. End uses of Dr Lin's technology.

4.3. Compatibility of AD Platforms with Emerging Technologies

Many configurations are possible using the AD platforms as base for a biorefinery. While the final possibilities for biorefining concepts will depend on feedstock availability, temporal variability of biomass, the business case, and local waste handling regulation, the LCA can be used a priori to inform about the environmental performance of the theoretical concepts. As examples, both 2StepPHA (Figure 4) and AD-Booster (Figure 5) are shown below with various experimental scale technologies attached on site, to create a cascading value chain. Figure 5 provides a full overview of the technological pathways for different feedstock, with different final products.

A value chain (Figure 4) with 2StepPHA could be constructed to process vine shoots and other agricultural wastes including wine pomaces. First, extraction of CT (1) from vine shoots and grape stalks is carried out and possible extraction of other polyphenols from wine pomaces. The vine shoots continue to process (3) to make biocomposites. The rest of the biomass is mixed with other agricultural wastes inside the Innoven plant and VFAs are produced. The VFA can either feed process (2) or continue to Innoven's own selection of biomass to make PHA. The choice to use (2) or the other can be informed by the LCA and will most likely depend on efficiencies. The products coming out of this biorefinery will be biogas, digestate, PHA, and various polyphenols (including at least CT) that can be used in several sectors.

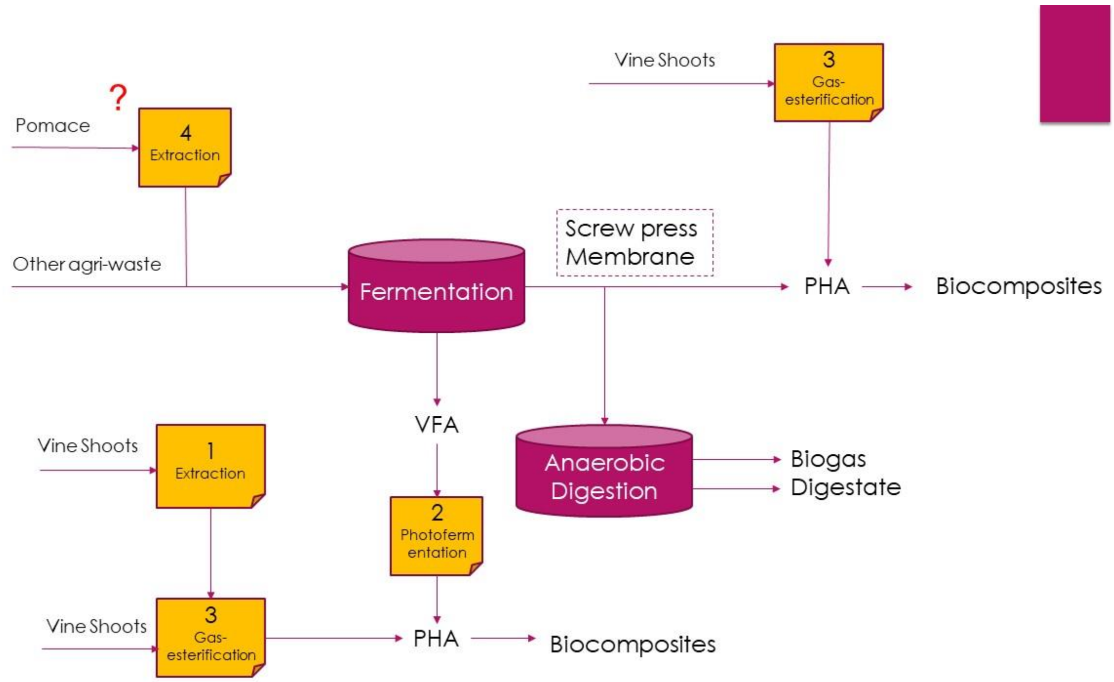

Figure 4. Possible value chain with Innoven's plant as base

A value chain (Figure 5) using the AD-booster technology will follow the same pathway as described for the 2StepPHA except the lignocellulose used in (3) will no longer be available, as it is mixed with animal manures, so it cannot be used to make biocomposites. It is possible that the amount of biocomposites with this configuration would be much lower, since only the processes that extract polyphenols and make biocomposites without the help of AD would be able to provide this service. The other products, biogas and digestate would have higher yields with this configuration.

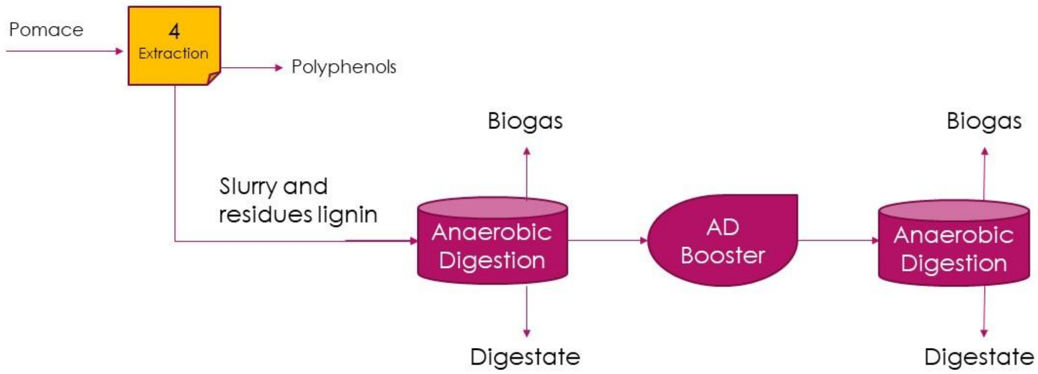

Figure 5. Possible value chain with AD-Booster technology

4.4 Building LCA scenarios and upgrading the analysis with Territiorial Metabolism

Methodology for assessing new technologies in a regionally specific context was developed and described by Croxatto Vega et al. (2019) and in NoAW deliverable D2.2. In D2.2 , the environmental impacts of integrating PHA production into biogas plants, relative to biogas production alone was assessed. It was pointed out that the addition of PHA production resulted in environmental benefits under all possible scenarios for all the regions in question. The next step, in order to provide a holistic picture of the environmental repercussions of NoAW technologies, is assessing biorefinery concepts that are compatible with the "AD Platform", potentially with PHA production as it was shown to be beneficial. To do this, assessments are performed at various levels. As a first simple step, compatibility was assessed for all technologies developed under the NoAW umbrella, with 3 main platforms as a starting point: the Innoven plant, the AD Booster enhanced biogas plant, and the NTUA plant, which are all TRL 6 and above.

The 3 platforms were assessed for compatibility with the following modules:

Module 1: Extraction and depolymerization of condensed tannins
Module 2: Lignocellulose filler material for biocomposites
Module 3: Photofermentation of PHA
Module 4: Extraction of Polyphenols
Module 5: CO_2 upgrade by biomass (Microbial Cell Electrolysis)

Table 1. Compatibility of modules with base technology

	Modules

	1	2	3	4	5
Innoven Biogas/PHA plant	x	x	±	x	x
Biogas plant with AD Booster	x	x	x	x	x
NTUA Ethanol Plant	x	o	o	x	x

± when this module is used, Innoven's own PHA selection is subtracted
x compatible
o not possible to combine

Secondly, additional branches of processing, hereby called "modules" are analyzed, first on an individual basis. In this stage, the aim is to obtain information at the process level, as for example, in (Croxatto Vega et al., 2019), where polyphenol extraction methods were analyzed to both pin-point environmental friendliness and optimize processing. The goal of this type of assessment is to provide information about which waste processing technology leads to the highest benefits. It is also possible to carry out a hot spot analysis to provide design recommendations.

Finally, innovative products resulting from the developed technologies are assessed at the product level. Here, the goal is to compare conventional products to the new products in terms of environmental impact e.g. trays made of biocomposites with lignocellulosic filler in comparison to conventional plastic trays.

4.4.2 The Functional Units

When doing an LCA, it is very important to choose the correct functional unit (FU). The choice of functional unit is a direct reflection of the aim of the study. However, when performing LCAs on biorefinery systems, the choice of functional unit is not straight forward, as has been debated by, among others, Ahlgren et al., 2013. In the NoAW project, the FU of choice when assessing multi-output biorefineries is 1 ton feedstock. This can be one single type of agricultural waste or a mixture. This FU was used in Croxatto Vega et al., 2019b and NoAW deliverable D2.2. In that case, the goal was to find out which technology brings about the largest benefits in terms of waste treatment in a specific region.

However, since the waste mixture will be different for each biorefinery, because different modules are bound to treat specific waste types, it is important to think of how to keep the assessment fair. According to (Ahlgren et al., 2013) it is quite common to use 1 biorefinery as FU or a combination of outputs from one biorefinery e.g. 1 MJ, 1 kg ethanol and 1 kg of bioplastic. This choice can be helpful when making a hotspot analysis or assessing if a stand-alone plant is better or worse than an integrated system.

Another option could be to shift the focus of the assessment to the products, in which case the question that will be answered will be “which products bring about the largest environmental benefits from 1 ton of waste processed”. The FU could be a X quantity of products (PHA, lignocellulosic filler) from the biorefinery obtained by treating 1 ton of waste.

Croxatto Vega et al., 2019 set the FU to be 1 kg of polyphenols in Gallic acid equivalents. In that study, the purpose was to compare the environmental and economic performance of different polyphenol extraction methods for the production of equal products. In the study by David et al. (2019), a tray of fixed volume was chosen as the FU.

4.4.3 Integrated assessment methods and decision support

The information generated by the LCA assessments at various levels is meant to be used iteratively to generate reliable and replicable decision support. This was described in detail in (Sohn et al., 2019) were information generated by LCA of laboratory methods was used for process optimization. In turn, processes were designed and optimized and TEA of the new processes was performed, followed by a complete LCA of the upscaled TEA optimized processes for polyphenol extraction.

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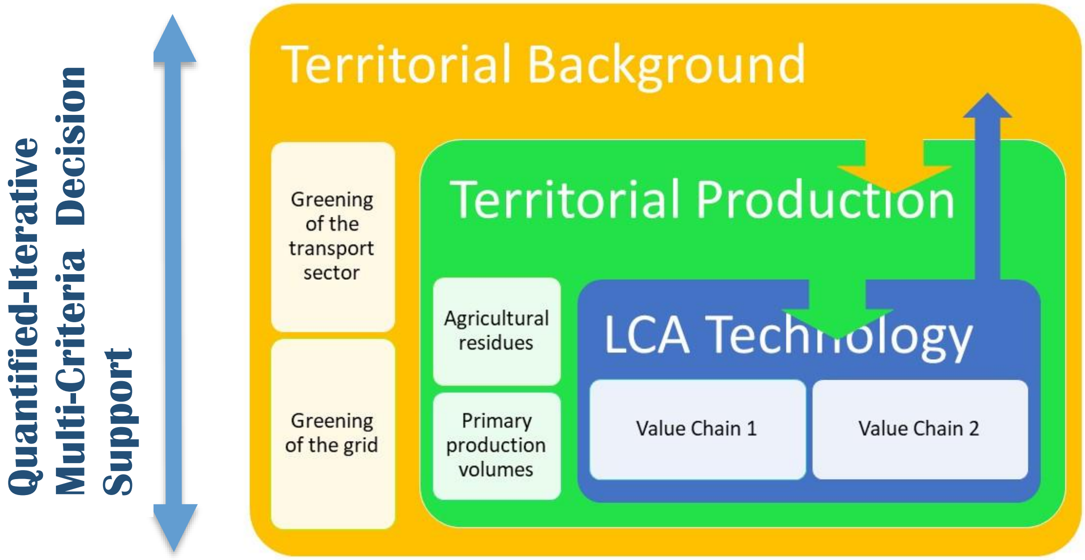

Figure 6. Visual representation of interaction between the life cycle assessment performed at various levels e.g. product level, process level, territorial level.

Figure 6 shows a visual representation of the iterative methods used for the assessment of NoAW technologies. The TM-LCA was applied largely in D2.2, while the assessment of extra modules has taken place for the individual technologies (blue area) always including the yellow area (background information of a specific geographical location.

The last step will be to assess how this type of production can be improved by handling its waste with the new technology or value chains (blue box in figure 6). In this way, the assessment is iterative.

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5. Evaluation of selected NoAW systems and technologies developed: Case studies

The following sections describe how assessments of NoAW technologies have been done and how these results can be used to create decision support. The work was done in collaboration with several NoAW WPs and partners. The first study is a life cycle assessment (LCA) of bio-composites produced from a polymer matrix and vine shoot filler. The second study is a combined LCA and Techno-economic assessment (TEA) and the third study shows how the LCA and TEA results can be turned into decision support.

5.1 Life cycle assessment of bio-composite packaging materials introducing vine shoots as fillers

(Summary of Manuscript by G. David et al., 2019)

5.1.1 Introduction and Methodology

One important pillar of the NoAW project is the production of bio-based and bio-degradable packaging materials from agricultural waste and residues. An example of such a technology is the production of bio-composite packaging materials. Practical work on bio-composites was carried out by the University of Montpellier within the frame of WP4.

Bio-based plastics are often more expensive than fossil-based alternatives which hinders bio-based plastics to increase their market share. Producing bio-composites by mixing a polymer matrix with a lignocellulosic fillers is one possible way to lower the price of bio-based and biodegradable packaging materials (Guillard et al., 2018). Biocomposites are generally considered as eco-friendly but very few studies quantify it. The aim of the here presented study was to assess the environmental effects of including lignocellulosic fillers in packaging trays. The fillers are made from vine shoots (ViSh) and the matrices are based on three different polymers, PHBV, PLA and PP. The study is made from a product perspective and the functional unit (FU) is a standard model tray with a volume of 25 cm^3, for single use packaging. The weight of the tray differs in the different scenarios assessed (due to the density of the materials). The scenarios represent 100% polymer trays and trays with ViSh fillers up to 30 vol%.

The trays are assumed to be produced and used in the Languedoc Roussillon (LR) region in France. LR is an important wine region and all vine shoots used in the production of trays are collected in LR. Vine shoots were considered as agricultural waste, and thus the ViSh production related processes were burden free since all the environmental impacts were allocated to the grape harvesting (Gullón et al., 2018). Data for the polymer matrices (PP and PLA) was taken from the Ecoinvent 3.4 database. Data for PHBV was taken from literature (Harding et al., 2007). Transport, energy and processing data were also taken from the Ecoinvent 3.4 databased and adapted to fit the studied case. The trays were produced after several steps: transports, dryings, millings, compounding and injection molding.

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End-of-life options were according to current waste treatment practices in France (ADEME, 2018). Waste treatment options included industrial composting, incineration with energy recovery, recycling and landfilling.

All background data of this study were from the Ecoinvent v.3.4 database with the Cut-off system model. The environmental impact assessment was done with the ReCiPe 2016 Midpoint Hierarchist (H) methodology and included all 18 impact categories.

5.1.2 Results

A detailed presentation and analysis of the results is given in the manuscript by David et al. (2019). This summary focuses only on the results for global warming.

When trays made from 100% polymer is compared, PLA has the highest impact to global warming and PP the lowest, despite being a fossil-based material. The environmental impact divided on the life cycle stages is shown in Figure 7. These results were explained by the fact that PP production is highly optimized with large tonnages contrary to bioplastics and PP density is lower than ones of PHBV and PLA.

Adding a vine shoot fillers reduced the contributions to global warming for all three matrices as is seen in Figure 8. Overall, the results show the value of using vine shoots from an economic and environmental point of view. It should be noted that trays with low filler content (< 5 vol%) have higher impacts than trays made of 100% plastic because an additional compounding step is necessary. There is therefore a filler content from which the composite tray becomes more interesting than the 100% plastic tray depending on the matrix considered. This filler content is 5.5 vol% for PLA and PHBV, it is 20 vol% for PP. For example, there is interest in using vine shoots in PHBV-based composite trays from filler content of 5.5 vol%.

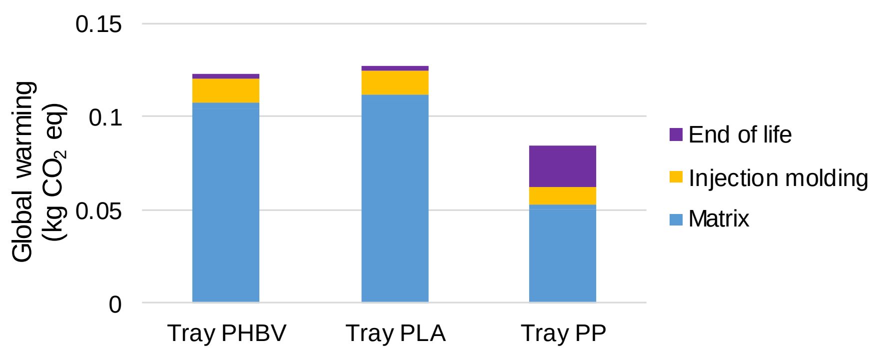

Figure 7. Global warming impact of one 100% plastic tray (without fillers)

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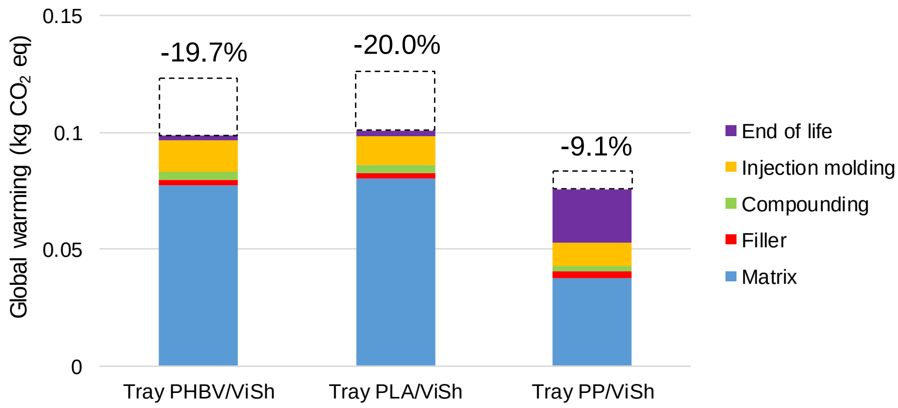

Figure 8. Global warming impact of trays with 30 vol% filler. The percentages above the bars indicate the reduction of the impact compared to trays without ViSh fillers.

It must be kept in mind that the risks associated with micro- and nanoparticles of plastic waste are not included in LCAs as it is currently impossible to quantify the effect of their accumulation. There is therefore more interest in producing PHBV-based trays (bio-based and biodegradable) than PP-based trays, although in Figures 7 and 8 suggest a benefit for PP. Indeed, PHBV-based composites are the only ones that are fully biodegradable in natural conditions.

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5.2 Lessons from combining techno-economic and life cycle assessment -a case study of polyphenol extraction from waste resources

The following section is a summary of a study by Croxatto Vega et al., 2019. The publication in its entity is included in Annex 1.

5.2.1 Methodology

The aim of the assessment was to provide early design guidance and information on the environmental impacts to the laboratories working with innovative polyphenol extraction methods (University of Bologna and Reasearch Institute of Sweden). In order to do so, a carbon footprint (CF) LCA was carried out of the extraction methods, assuming the yields obtained in the lab could be maintained, but using industrial scale equipment and flows. The methods analyzed were: solvent extraction using acetone and water as solvent (S-Acn), pressurized liquid extraction using ethanol and water as co-solvent and supercritical CO_2 (PLE-EtOH-75), and liquid extraction using ethanol and water as solvent (PLE-EtOH-100). An additional extraction using 100% supercritical CO2 in a first step, before the co-solvent step with ethanol and water, was also analyzed (PLE-EtOH-oil). The results obtained from the CF were used to pinpoint hotspots and optimize process flow design at the industrial scale. The optimization was carried out with the process flow software Superpro Designer were TEA was also performed. The results from the optimization and TEA were used for a second iteration were an LCA with all environmental impact indicators were obtained.

5.2.2 Results

The CF of laboratory methods (without optimization) showed clearly that high amounts of solvent use result in a high carbon footprint. It was evident that a pressurized system, such as the one used for PLE-EtOH-75 incurred high burdens during extraction, due to high energy needed for distillation and pressurization of the system, which had a large liquid flow. Thus, optimization of the methods focused on reducing solvent amounts by adding extraction steps in a counter-current flow.

Optimized systems for solvent extraction and PLE were assessed through a techno-economic assessment. Results showed the PLE option with the lowest solvent to dry weight ratio of 5 to be the cheapest in producing cost (5.6€/kg polyphenol), this was despite having higher fixed capital cost which are compensated by a higher extraction yield (Figure 9). The next best option was solvent extraction using acetone with a DW ratio of 2 (7.9 €/kg).

Results from the LCA with all indicators matched the TEA, were PLE-EtOH-5 was the best performing option in terms of global warming potential and also other environmental impact indicators. However, the S-Acn-2 scenario was also shown to be a competitive option, when the average environmental score is taken into account, but not when the decision is based only on GWP indicator. Thus, the assessment shows that it is necessary to refine the interpretation of results by potentially adding MCDA methods, so that a decision can be made, based on the results (Figure 10).

It is also noteworthy to mention, that after a roundtable discussion with the technology developers, the technical feasibility of the options assessed was discussed. It was made evident that some of the options, were not within what is considered feasible solvent to DW ratio due to constraints from scale up equipment. This necessitated adding more options to the assessments and rerunning the assessments. The final decision after this iteration was solvent extraction with acetone. When solvent to DW ratios were adjusted (increased) according to equipment limitations, the S-Acn option showed to be the best performing from both an economic and environmental standpoint.

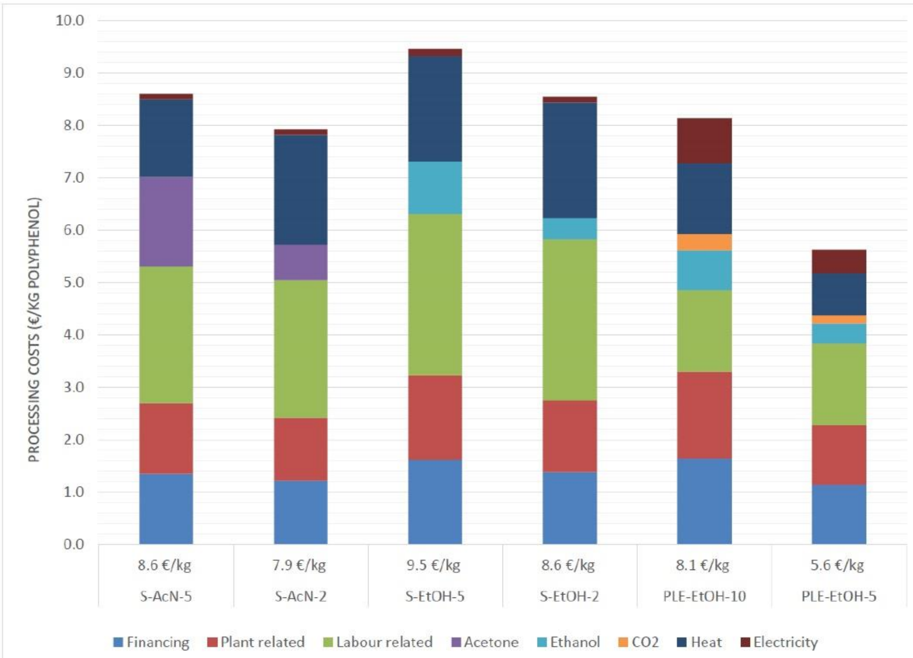

Figure 9 Techno-economic assessment results of optimized polyphenol extraction at industrial scale

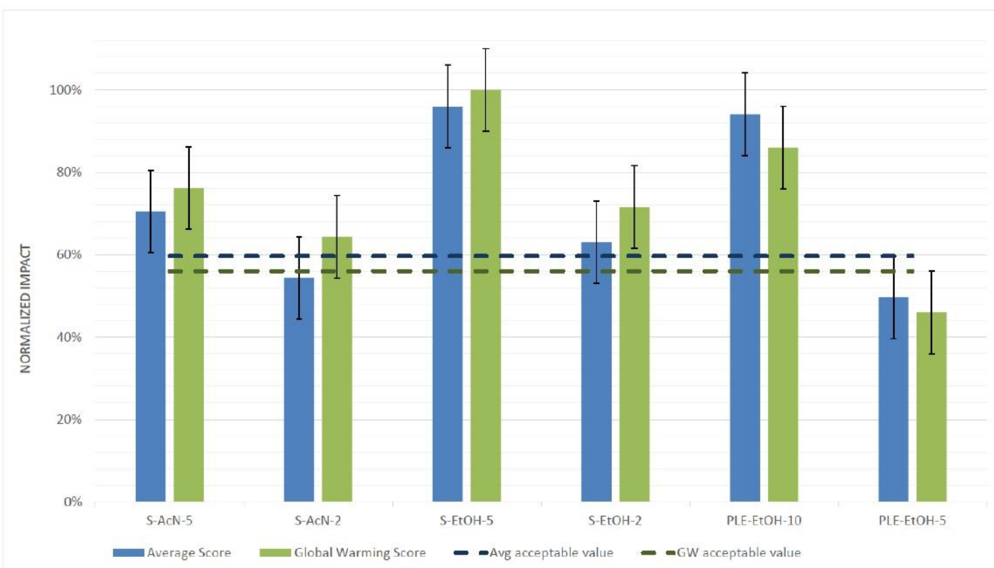

Figure 10 Single score impact results from the full LCA. Single scores are derived by internally normalizing results to the worst performing scenario and averaging all impact categories into a single score (blue bar). While for GWP, internally normalized results for each scenario are shown (green bar). An arbitrary uncertainty value of ±10% is depicted for each single score by the dashed lines, to show distance to the best solution. Error bars also show ±10% uncertainty level.

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5.3 Incorporating relative importance: selecting a polyphenol production method for agro-waste treatment in an environmental and economic multi-criteria decision making context

The following section is a summary of a study by Sohn et al., 2019. The publication in its entity is included in Annex 2.

5.3.1 Introduction

In the context of the NoAW project, many technologies are being developed. And, there are many potential regions for implementation of said technologies. In order to come to a determination of the best possible solutions (value chain, technology, etc.) there must be a metric of comparison. Utilizing techno-economic assessment and life cycle assessment, various technologies have been assessed, and in this case, various technologies for polyphenol production. This assessment has resulted in 19 criteria by which the various technology alternatives are tested. These include pressurized liquid extraction (PLE) and solvent extraction (S) with ethanol (EtOH) and acetone (Acn) at various dry matter (DM) to liquid ratios. In order to allow for harmonization of these multiple criteria, a framework for including relative importance in developing a weighting system for application in multiple criteria decision assessment (MCDA) is proposed and implemented.

5.3.2 Methods

In order to derive a relative importance of the various environmental criteria, a relative importance factor (RIF) is calculated based on the level of impact present in the assessed environmental criteria in relation to annual per capita emissions. It is noted that relevance to planetary boundaries would be preferred, but this is considered not technically feasible at present. This RIF is then used to derive a weighting string, which is applied to the various alternative scenarios in an MCDA utilizing the technique for order of preference by similarity to ideal solution (TOPSIS). This is carried out for all scenarios, though some are eventually discarded due to technological limits.

5.3.3 Results

Based on the analysis from TOPSIS, a preference depending on the level of importance given to economic performance can be derived (Figure 11). PLE with a solvent to DM ratio of 10:1 and S with a solvent to DM ratio of 5:1 are called out as the two competing scenarios based on technological feasibility along with environmental and economic performance. The determination of the preferred technology is dependent on the weight given to economic performance relative to environmental performance, with the preference order reversing at appx. 50% weight to economic criteria when utilizing RIF.

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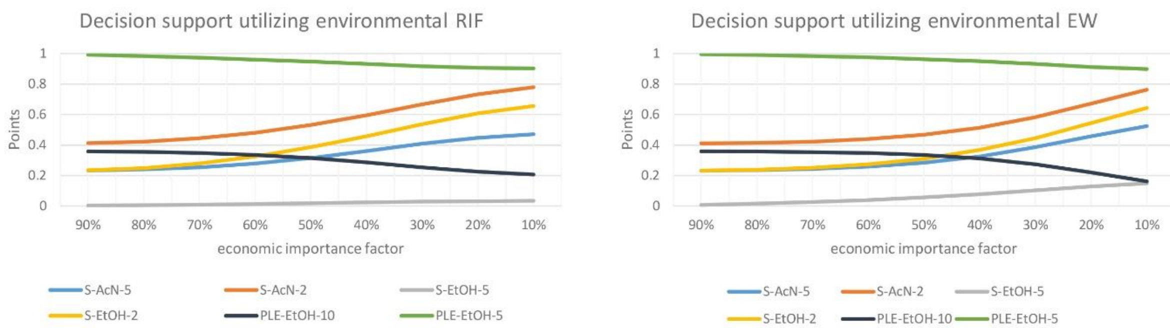

Figure 11: TOPSIS derived single score indicator of idealness (most ideal=1) for both RIF derived environmental weighting and EW environmental weighting amongst a range of EIF

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6. Discussion and Conclusions

This deliverable shows examples how environmental assessments have been performed in the NoAW project and how the results can be developed into decision support. The technical feasibility study shows the background and the process that was applied in order to choose case studies from the vast number of technologies developed in the NoAW-project.

This deliverable focuses on technologies that have been developed in a laboratory scale but that are mature enough for upscaling. Decision support described here was applied to guide the decision regarding the upscaling of technologies in the NoAW project. Decision support is based on MCDA and takes a number of environmental and economic factors into account.

7. Partners involved in the work

The partners directly involved in this work are, RISE, DTU and INRA. WUR also contributed to the studies presented in the deliverable.

8. FAIR Data management

The data that this report is based on has been presented in previous publications cited in the report and Annexes.

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10. Annexes

Annex 1

Lessons from combining techno-economic and life cycle assessment – a case study of polyphenol extraction from waste resources

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1. Introduction

Biomass demand for the production of bioenergy, biomaterials and biochemicals is estimated to increase by 70-110 % by 2050 compared to 2005 level [1]. A paradigm shift to renewable sources of production has for long been discussed, in the context of circular economy and valorization of biomass waste resources produced through the agricultural value chain. The bioeconomy today is valued to have a 2.4 € billion turnover, which is only expected to increase in the future [2]. Yet, the prefix bio does not guarantee sustainability. For example, growing biomass for biofuels has long been debated, prompting the Renewable Energy Directive [3] at a European level to ensure validity of greenhouse gas reductions claims. In this regard, integration of quantitative sustainability assessment such as life cycle assessment (LCA) and techno-economic (TEA) assessment have been regarded as valuable. Combined TEA-LCA has been applied in many occasions to assess the environmental and economic ramifications of implementing new technologies. Among many of the aspects studied are; the novel use of lignocellulosic

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material for production of biodiesel from palm oil residues [4], production of biofuels and bioresins [5], and bioblend stocks for the light and heavy-duty transport [6]. More interestingly, TEA-LCA has been used for quantifying externalities in the form of Disability Adjusted Life Years (DALY) to provide a more complete picture of the financial burdens arising from environmental problems [7]. Recently, combining TEA and LCA has been used to optimize new production routes from an early design phase, such as the integration of wastewater into microalgae production for biodiesel production [8], or the integration of power-to-gas technology of methane and photovoltaics [9]. Combining TEA and LCA lends itself well to finding production hot spots and opportunities for optimization. This is even more relevant when applied to renewable resources such as biomass, which have to be managed sustainably.

Agricultural residues are an increasingly important biomass resource, which continues to be studied to increase maturity level of 2G and 3G production. In this context, the No Agricultural Waste H2020 NoAW project is working towards the development of sustainable value added products from agricultural residues, such as biocomposites, biodegradable bioplastics, and more [10]. Among these, wine pomace is a residue rich in polyphenols, which are compounds with high antioxidant value [11]. Polyphenol extraction methods at the laboratory scale can be analyzed using TEA-LCA in order to identify hotspots and potentially environmentally problematic production steps. Therefore, in this study LCA is applied at an early design stage to obtain a preliminary carbon footprint of the polyphenol extraction methods. Subsequently, TEA-LCA is applied in simulated industrial conditions, optimized with guidance from literature and the preliminary LCA. The goal is to obtain a holistic picture of the economic feasibility and possible environmental impacts determined by each polyphenol extraction method.

2. Methodology

In short, results of laboratory scale experiments of different methods for the extraction of polyphenols from red grape pomace were evaluated using a combination of LCA and TEA. Based on the preliminary LCA of the laboratory scale experiments, industrial scale processes were designed. The industrial scale processes were, thereafter, analyzed with both LCA and TEA.

2.1 Polyphenol extraction methods and laboratory experiments

Various polyphenol extraction methods developed within the NoAW project were assessed. The extraction methods include both solvent extraction and pressurized liquid extraction (PLE).

2.1.1 Extraction with acetone – S-AcN

Batch extraction was performed in the laboratory with 75% acetone, 25% water as solvent, with a solvent to dry weight (DW) ratio of 11. Extraction was performed in an air tight vessel at 50°C at atmospheric pressure. The solvent and pomace were kept in contact for 2 hours after which time the polyphenols have been dissolved in the liquid phase from where they can be isolated and obtained as a powder. The polyphenol content was then analyzed. This set up was also tested for 1 and 4 hours.

2.1.2 Extraction with ethanol – S-EtOH

The same procedure as in 0 was tested with ethanol as solvent. Equal parts ethanol:H_2O were used for the extraction. Extraction times of 1, 2 and 4 hours were tested to observe their influence on yield. The S-EtOH was only examined assessed at industrial scale (section 0 and 0).

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2.1.3 Pressurized liquid extraction with ethanol – PLE-EtOH

Three different options for PLE were studied in the lab. PLE-EtOH-75 with 75% co-solvent composed of equal parts ethanol and water and 25% liquid CO_2. PLE-EtOH-100 is performed without liquid CO_2 and instead there is 100% co-solvent composed of equal parts ethanol and water. The extraction is performed at 80°C and 100 bar. While the third PLE option, PLE-EtOH-oil, is divided into two extraction steps. One with 100% supercritical CO_2 at 350 bar and 80°C for one hour, with a flow of CO_2 of 30g per minute, leading to the production an oily phenolic extract. A second extraction step with the same $EtOH:H_2O:CO_2$ ratio as applied for PLE-EtOH-75 is performed to obtain polyphenols as dry extract. The solvent flow for the second step was 8g per minute. As this is a continuous set up, both of these steps lead to an extremely high solvent to DW ratio. All extraction operational parameters are presented in Table 1.

All extraction processes listed leave behind the pomace residue, which can be further valorized using different methods not tested in this study [10].

Table 1 Operational parameters of laboratory experiments.

Laboratory Conditions				
Scenario Name	S-AcN	PLE-EtOH-75	PLE-EtOH-100	PLE-EtOH-oil
Yield (g polyphenol/kg DW)	47	48	44	49
Solvents				
Acetone	75%			
Ethanol		37.5%	50%	37.5%**
Water	25%	37.5%	50%	37.5%**
CO_2		25%		100%*, 25%**
Solvent to DW ratio	11	101	101	583
Extraction				
Stages (no.)	1	1	1	2
Duration (minutes)	120	30	30	90
Temperature (°C)	50	80	80	80
Pressure (bar)	1	100	100	350*, 100**

*first stage
** second stage

2.2 LCA of laboratory scale experiments

A preliminary LCA was performed on the extraction methods described above, using only the Global Warming potential (GWP) impact category as the main indicator. The ReCiPe 2016 Midpoint Hierarchist method [12], which has a 100 year time horizon from point of emission, was used as impact assessment method, supplied by the Ecoinvent 3.4 Database [13]. The functional unit for the LCA is 1 kg of polyphenols. The process design software, Superpro designer [14], was used to simulate the polyphenol extraction methods with industrial scale equipment. However, all operating parameters such as temperature, solvent to DW ratio, polyphenol yield, pressure, and extraction times among others, were kept equal to laboratory conditions (Table 1). Simplified flow diagrams with the industrial equipment used are shown in Figure 1 and Figure 2. The polyphenol producing plant is assumed to be placed in Italy and thereby, background processes for Italy from the Ecoinvent database were used as much as possible, e.g. the electricity grid.

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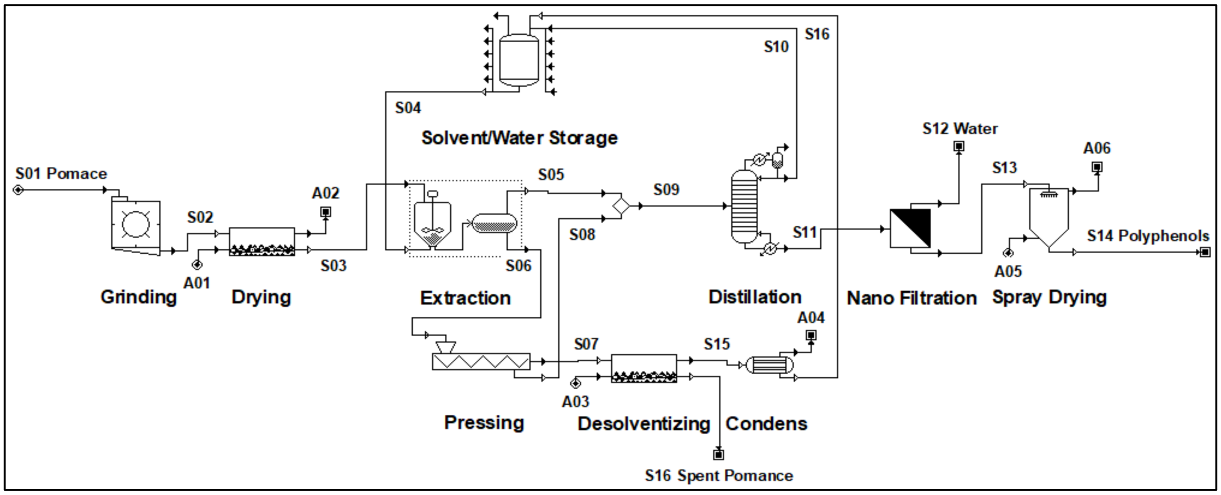

Figure 1 Solvent extraction with either acetone or ethanol at atmospheric pressure. The pomace dryer is optional.

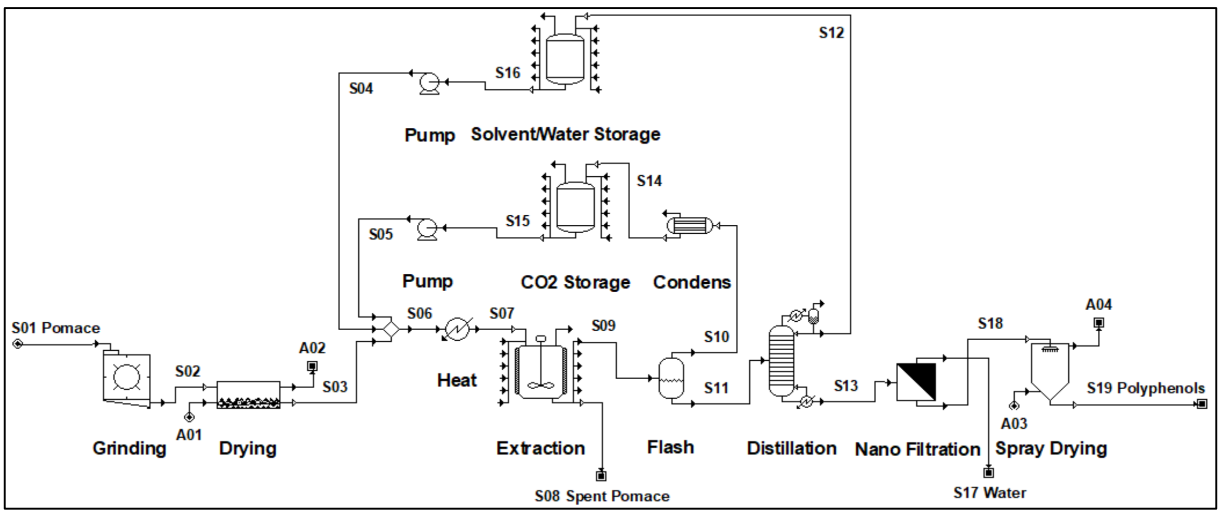

Figure 2 Pressurized liquid extraction with ethanol, water, and supercritical CO_2. The pomace dryer is optional.

2.3 TEA of industrial scale processes

Based on the results of the laboratory scale experiments, the preliminary LCA, and literature [15]–[19], industrial scale processes for solvent extraction and PLE were designed. TEA of the industrial scale processes designed was carried out in order to investigate the economic repercussions of installing a polyphenol extracting plant. The TEA includes Capital Expenditure (CapEx) and Operating Expenditure (OpEx). Assumptions and simplifications were made in order to fill data gaps. Assumptions of economic parameters and estimates of fixed capital costs were based on [14], [20]–[23].The most important assumptions are reported in Table 2.

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Table 2 Parameters for the techno-economic assessment.

Production	8000	h/y
Red pomace	20	kton wet/y
	2500	kg wet/h
	36%	DW
Labour related costs	891	k€/y
Plant related costs	10%	of fixed capital/y
Financing costs	10%	of fixed capital/y
Electricity	0.1	€/kWh
Steam	25	€/ton
Ethanol price	0.8	€/kg
Acetone price	1.2	€/kg
CO_2 price	0.5	€/kg
Solvent loss	2%	of recycle
Energy solvent recycle	2	x ΔH vap
Heat of vaporization ΔH		
Water	2260	kJ/kg
Ethanol	841	kJ/kg
Acetone	539	kJ/kg
CO_2	380	kJ/kg

The labour related costs were assumed to be the same for all processes and are based on: 2 shift positions, an operator salary of k€ 30/y including supervision, direct salary overhead, and general plant overhead. The plant related costs include maintenance, tax, insurance, rent, overhead, environmental charges, and royalties. The financing costs are based on an amortization of the fixed capital costs over 10 years with no interest.

For all processes, a solvent loss of 2% of the solvent in the recycle is assumed. The energy which is required to recycle the solvent is estimated as two times the heat of evaporation. For the recycle of water, acetone, and ethanol, thermal energy is required, while for the recycle of CO_2 electricity is required.

2.4 LCA of industrial scale processes

Following the TEA, a complete accounting LCA was performed on the same systems analyzed for the TEA. The system boundary for the accounting LCA includes all actions carried out in order to obtain 1 kg of polyphenols from when the grape pomace enters the production system to the product leaving the production facility, e.g. all processing steps, such as grinding, drying, adding solvents, filtering, distillation and more (Figure 1 and Figure 2). On the other hand, the “gate-to-gate” LCA does not include end of life of the polyphenols or any transport throughout the life cycle. Furthermore, no allocation is performed, i.e. the entire burden of production is assigned to the main product, the polyphenols. Likewise,

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no credits are assigned for the production of polyphenols potentially replacing similar products in the market.

The LCA includes all 18 impact categories in ReCiPe 2016 Midpoint (H) methodology. As for the LCA at lab scale, the geographical location of the polyphenol plant is assumed again to be Italy.

To ease interpretation of results, a simple multi-criteria decision support assessment (MCDA), was performed. First, results for the 18 impact categories were normalized within each impact category to the worst performing scenario and ranked. Second, normalized results were averaged to obtain a single score per scenario, which was then used to single out the best performing scenario. The average results were compared with Global Warming results in order to assess the possibility of burden shifting between other environmental problems (categories).

3. Results

3.1 LCA of laboratory scale experiments

The carbon footprint analysis clearly shows that if laboratory conditions are maintained when implementing a polyphenol extraction plant, then the acetone based solvent extraction method outperforms all other scenarios by a large margin, in terms of global warming potential (GWP). This is largely due to the amounts of solvent used in each scenario, which are lowest for the S-AcN scenario. The large amount of solvent used in the continuous set up for all PLE scenarios results in a very high electricity and heating demand in, for example, electricity for compressing of the system, heating during polyphenol extraction, and heating during distillation to recover the solvents.

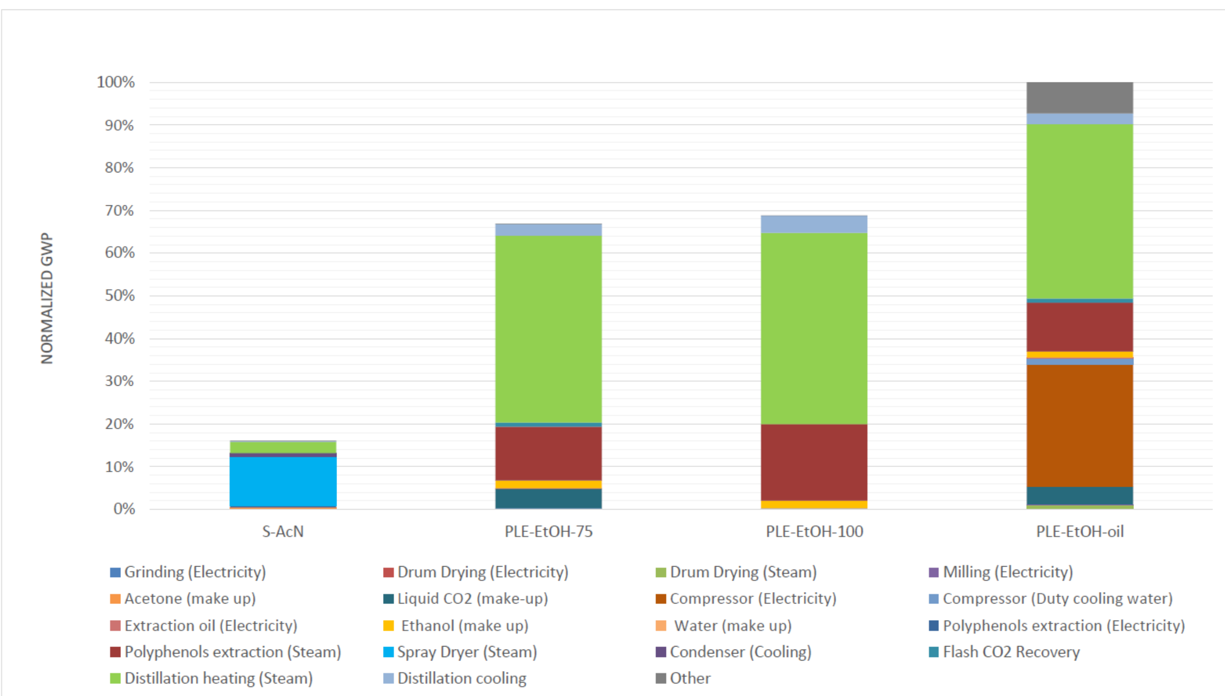

Figure 3 Normalized global warming potential results of polyphenol extraction scenarios at lab scale. Functional unit is 1 kg of polyphenols. Normalization to worst performing scenario PLE-EtOH-oil.

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From the preliminary LCA, the importance of keeping the solvent ratio as low as possible is evident. This has a trickle down effect on the energy demand of the whole system. It was also proposed that the contact between solvent and pomace could be increased by changing the set up of the system. Systems with multiple extraction stages and lower solvent to pomace DW ratios were considered in the TEA.

3.2 TEA of industrial scale processes

The TEA focused on optimizing the operational parameters so that it would be economically feasible to implement a polyphenol extraction at industrial scale. Based on laboratory scale experiments and literature [15]–[19], extraction steps were increased and as a result the solvent to pomace DW ratios decreased. Because water is already present in the pomace, it is necessary to dry the pomace prior to the extraction to maintain a solvent to DW ratio of 2 (S-AcN-2 and S-EtOH-2). Total extraction time was assumed to be 60 minutes for all processes. Equipment was scaled based on the flow sizes and subsequently the purchased equipment costs and fixed capital costs were estimated. The operational parameters and assumed extraction yields are given in Table 3.

Table 3 Operational parameters of designed industrial scale processes.

	Industrial Scale					
Scenario Name	S-AcN-5	S-AcN-2	S-EtOH-5	S-EtOH-2	PLE-EtOH-10	PLE-EtOH-5
Yield (g polyphenol/kg DW)	47	47	40	40	79	79
Solvents						
Acetone	67%	67%				
Ethanol			50%	50%	37.5%	37.5%
Water	33%	33%	50%	50%	37.5%	37.5%
CO_2					25%	25%
Solvent to DW ratio	5	2	5	2	10	5
Extraction						
Stages (no.)	2	5	2	5	2	2
Duration (minutes)	30	60	60	60	60	60
Temperature (℃)	50	50	50	50	80	80
Pressure (bar)	1	1	100	100	100	100

The best performing scenario, in economic terms, is PLE-EtOH-5, which also has the highest polyphenol extraction yield. Despite lager fixed capital costs, the costs expressed per kg polyphenol are lower compared to the solvent extraction processes Figure 4. The second best scenario is S-AcN-2, which has the advantage of a low solvent to DW ratio of 2 and similar cost range for plant related and financing cost. However, the heat demand for S-AcN-2 is larger, because drying of the pomace is required.

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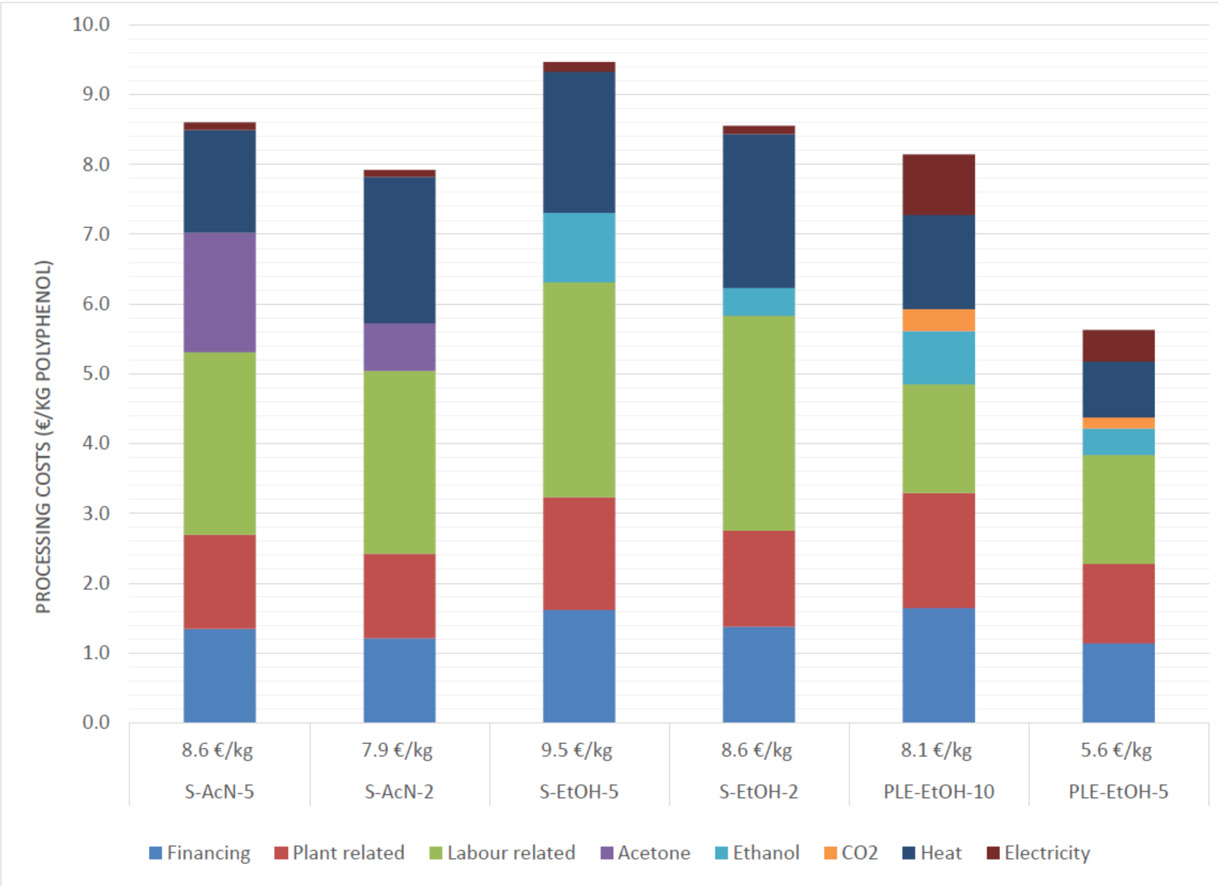

Figure 4 Techo-economic assessment results of optimized polyphenol extraction at industrial scale.

3.3 LCA of optimized industrial scale design

The LCA of optimized operational conditions showed that if seeking to alleviate environmental problems it would be preferable to choose PLE-EthOH-5, that is to say, a pressurized extraction that uses ethanol, water and supercritical CO_2 as solvent, with a solvent ratio of 5 and 2 extraction steps (blue bars, Figure 5). It is noteworthy to say that a solvent extraction using acetone with a solvent ratio of 2 (S-AcN-2) is potentially within the same range of impact when all impact categories for the LCA are equally weighted i.e. all environmental problems encompassed in the LCA are equally valued. If instead, the goal is to reduce global warming at the potential cost of other environmental problems, then the best choice is PLE-EthOH-5, and S-AcN-2 is possibly acceptable when considering the lower bar of uncertainty, here judge to be ±10%.

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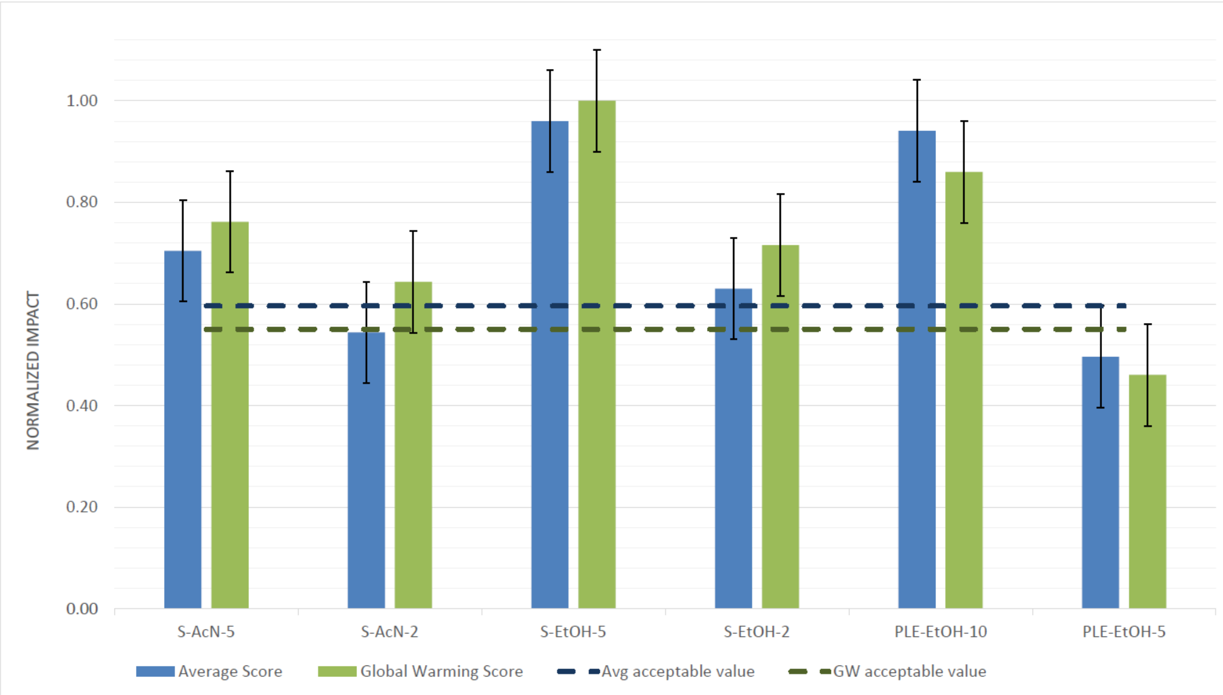

Figure 5 Single score impact results from the full LCA. Single scores are derived by internally normalizing results to the worst performing scenario and averaging all impact categories into a single score (blue bar). While for GWP, internally normalized results for each scenario are shown (green bar). An arbitrary uncertainty value of ±10% is depicted for each single score by the dashed lines, to show distance to the best solution. Error bars also show ±10% uncertainty level.

Furthermore, results from the TEA align well with the LCA, which points out that, at least in this case, the same parameters that are "expensive" for the environment, are also costly for the investment.

4. Discussion

The preliminary LCA assessment performed on the lab scale emerging technologies can be used in the early design phase, in order to avoid excessive environmental burden later on. By identifying hot spots early on, it is possible to envision adjustments to the production set up, so that the identified hot spots are addressed. In this case, the environmental hot spots coincide well with economic costs, as is shown by the successive TEA-LCA. For both of these assessments, one of the most important parameters was solvent to wine pomace dry weight ratio. High use of solvent leads to high operational costs and increase demand for electricity and heat, which affect the results of both TEA and LCA. On the other hand, higher yields allow more leeway for higher energy consumption. This is observed in the results for PLE-EtOH-5, which has a very high electricity demand, due to the compressed system, but at the same time produces one of the highest yields out of the assessed scenarios. The high yield translates into reductions in the energy demand when looking at the results on a per kilo of product basis.

Results for the TEA showed that increasing the number of extraction steps has consequences for vessel volumes, which can be kept smaller if there is a higher number of extraction steps. In turn, this results in lower fixed capital costs for the extraction. On the other hand, to keep solvent ratios low it is necessary to add a drying step before mixing the wine pomace, which contains water in itself. The extra drying incurs extra costs for heating, while at the same time saving some costs for material expenditure. These results are mirrored in the LCA, where results benefit from lower solvent use, while impacts are increased due to the extra heating needed. In this regard though, it was clear in the LCA that solvent use, especially if the solvent is acetone, comes with higher impacts than electricity or heat use. This is easily illustrated when looking at the GWP impacts of 1 kg of acetone compared to 1 kg of ethanol or 1 kwh of electricity, as shown in Figure 6, but also when looking at other impact categories (not shown here). From this figure it is possible to visualize that, in terms of the overall assessment, added acetone or ethanol weigh more than added heat or electricity, with acetone being two times more burdensome than ethanol.

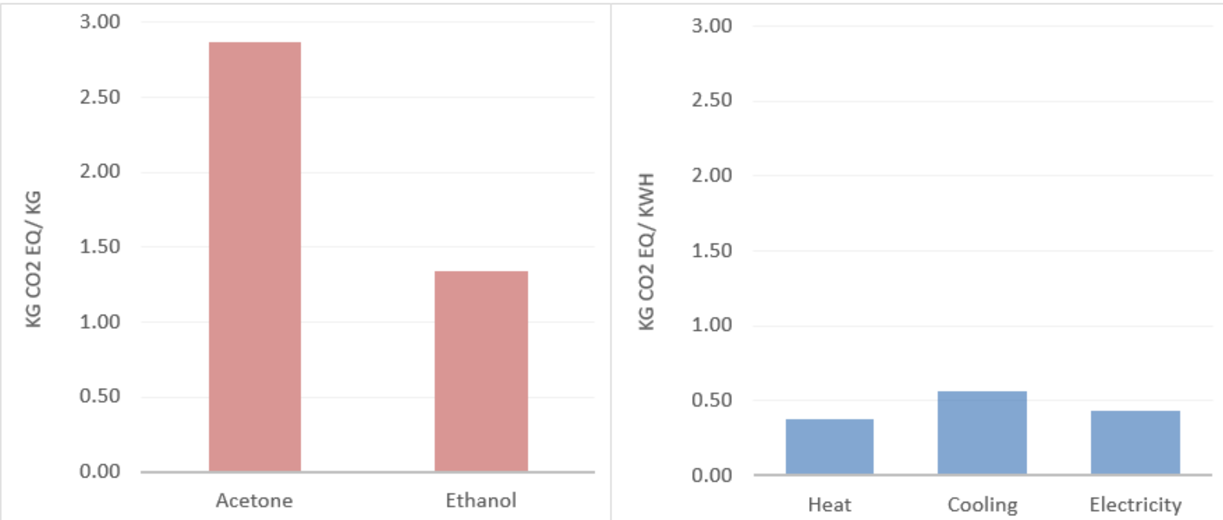

Figure 6 Global warming potential of 1 kg of acetone or ethanol. GWP of 1kWh of cooling, Italian electricity or heating. For illustrative purposes.

In this regard, it is also worth mentioning that the ethanol used for this assessment is of petrochemical origin. However, since the waste being treated is wine pomace, it is quite possible that a biorefinery treating this waste would also produce ethanol. This is true for distilleries placed in Italy and France, which currently treat wine pomace in order to produce ethanol, bioenergy and food additives, among other.

The TEA in this study considers the processing costs including the financing costs. The market price of the product, the extracted polyphenols, and the market volume are yet to be explore. Once a market price or price range is known, then fixed capital costs and processing costs can be compared to the benefits, and profitability indicators such as, net present value (NPV) and internal rate of return (IRR) can be taken into consideration. A larger investment for more complex technology (PLE instead of solvent extraction) might be justified if the benefits are significantly lager.

Besides the economic (TEA) and environmental (LCA) aspects investigated, it is also useful to consider the technology readiness level (TRL) of the evaluated processes. Solvent extraction, with both acetone and ethanol, is a mature process technology, which is currently implemented at large scale. PLE is a less mature technology for which extra measures might be required for large scale implementation.

5. Conclusion

Polyphenol extraction methods developed in the NoAW H2020 project were assessed using LCA at different maturity levels and with TEA-LCA at industrial scale. The lab scale results highlight the need to reduce solvent use and maximize yields. The TEA-LCA point towards the same extraction method, that is a pressurized liquid extraction, using CO2:EtOH:H2O as solvent with a solvent to DW ratio of 5, and 2 extraction steps. If the same yields can be attained with these conditions then this option leads to the highest environmental and economic benefits, despite higher CAPEX. The most important parameter for optimization of the LCA results is reducing solvent amounts. The most important parameters of the TEA are the polyphenol extraction yield and the solvent to DW ratio.

Acknowledgements

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Annex 2

Incorporating Relative Importance: selecting a polyphenol production method for agro-waste treatment in an environmental and economic multi-criteria decision making context

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Abstract

Purpose: The No Agricultural Waste project is faced with selecting the best alternative amongst six extraction methods for polyphenol production used to upgrade agricultural residues.

Methods: In order to complete this, a multiple criteria decision assessment method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), is applied to results for the six extraction methods from techno-economic assessment and life cycle assessment carried out previously in the project. A normalization-based method of relating the weighting applied in the MCDA to the relative importance of environmental impacts in the assessment is applied, and decision support is provided for various levels of weight given to the economic impacts of the system.

Results: One clear ideal alternative, a pressurized liquid extraction method using Ethanol, Water & $SCCO_2$ solvent with a solvent ratio of 5, is specified, along with a second best alternative using acetone and water and a solvent ratio of two. The third best alternative depend on the weight given to economic impacts and the weighting applied amongst environmental impacts.

Conclusions: It is concluded that apart from the ideal alternative and the second ranked alternative, the third ranked alternative depends on the weight given to the economic indicator. Furthermore, the application of the relative importance factor for environmental criteria as a method of deriving weighting reduced the influence of criteria with impacts that are relatively unimportant in absolute terms.

1. Introduction

When policy makers, corporations, or any other actor is faced with the need to choose between alternative solutions to a given problem, there is often a multitude of issues to be taken into account. And, the decision-making context surrounding such a choice can be handled in many ways, from community-based decision making to round table discussions or even executive fiat. However, without a tool for handling fundamentally conflicting information, the results of decision making through discussion can vary wildly and may depend on happenstance and or subjective factors. Since its primary foundation in

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in the 1950's, Multiple Criteria Decision Analysis (MCDA) has been applied to aid in alleviating these problems by introducing a transparent and repeatable form of decision support [1].

When looking at environmental issues in life cycle assessment (LCA), oftentimes practitioners turn to single indicators such as global warming potential (carbon footprinting), but this poses potential downfalls such as burden shifting (e.g. shifting environmental burdens from carbon emissions to environmental or human toxicity) [2]. In other cases, practitioners turn to endpoint damage modeling, but these have high levels of uncertainty and still leave the decision maker with several categories of environmental damages (e.g. ecosystem health, human heath, and resource availability). Furthermore, neither of these methods can be directly combined with economic indicators. In some cases, LCA practitioners have monetized impacts in order to combine environmental and economic indicators, however these suffer from issues, among others, involving the relationship of internalized and externalized costs [3]. These issues have lead some LCA practitioners to turn to MCDA for providing decision support [4–6].

When applying many types of MCDA, though, there is one element that has a determining effect on decision support, namely weighting. In this paper, MCDA is applied to the decision context of a European Union Horizon 2020 project, No Agricultural Waste (NoAW), choosing between various developed technologies for extracting polyphenols as a means of upgrading agricultural wastes to agricultural co/by-products. A weighting-profile derivation framework is proposed in order to incorporate the relationship between the various environmental impact criteria that are the result of life cycle assessments and an absolute reference point for environmental impacts in order to avoid making a decision based on irrelevant criteria. The criteria from LCA and an economic analysis are then incorporated to provide decision support for selecting a technology for scale-up in the NoAW project.

2. Methodology

2.1 Definition of the case

The NoAW project will be selecting a technology for polyphenol extraction to undergo further testing at pilot scale, after having developed a number of extraction methods at lab scale. These include both processes using acetone and ethanol as a solvent (Table 1) and are further described in [7]. Amongst these six alternative extraction methods, one must be chosen for upscaling; however, due to the potential for technical issues, a second and third choice method for upscaling should also be chosen. Attributes of the various extraction methods are available in the form of ReCiPe 2016 [8] midpoint environmental impacts and a production cost that is obtained via a techno-economic assessment.

Table 1: Description of assessed alternative extraction methods with ReCiPe 2016 midpoint impacts and production cost shown per kg of gallic acid production [7]

	Solvent Extraction				Pressurized Liquid Extraction		
	Acetone & Water		Ethanol & Water		Ethanol, Water & $SCCO_2$		
	340 ton GA/y		290 ton GA/y		572 ton GA/y		
	solvent ratio: 5	solvent ratio: 2 (dryer required)	solvent ratio: 5	solvent ratio: 2 (dryer required)	solvent ratio: 10	solvent ratio: 5	
Impact	**S-AcN-5**	**S-AcN-2**	**S-EtOH-5**	**S-EtOH-2**	**PLE-EtOH-10**	**PLE-EtOH-5**	Unit
Fine particulate matter formation	2.26E-02	1.93E-02	2.81E-02	2.08E-02	2.62E-02	1.41E-02	kg PM2.5 eq
Fossil resource scarcity	1.13E+01	8.97E+00	1.43E+01	9.87E+00	1.20E+01	6.42E+00	kg oil eq

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Freshwater ecotoxicity	3.09E-01	1.77E-01	4.63E-01	2.36E-01	4.38E-01	2.24E-01	kg 1,4-DCB
Freshwater eutrophication	3.47E-03	2.56E-03	5.27E-03	3.21E-03	5.26E-03	2.75E-03	kg P eq
Global warming	3.23E+01	2.73E+01	4.24E+01	3.03E+01	3.64E+01	1.95E+01	kg CO2 eq
Human carcinogenic toxicity	4.24E-01	2.89E-01	5.69E-01	3.40E-01	5.37E-01	2.80E-01	kg 1,4-DCB
Human non-carcinogenic toxicity	8.07E+00	4.77E+00	1.23E+01	6.36E+00	1.16E+01	5.95E+00	kg 1,4-DCB
Ionizing radiation	7.36E-01	7.00E-01	1.05E+00	8.05E-01	1.41E+00	7.48E-01	kBq Co-60 eq
Land use	1.97E-01	2.23E-01	2.93E-01	2.53E-01	3.42E-01	1.85E-01	m2a crop eq
Marine ecotoxicity	4.70E-01	2.85E-01	6.98E-01	3.71E-01	6.51E-01	3.35E-01	kg 1,4-DCB
Marine eutrophication	2.30E-04	1.80E-04	3.40E-04	2.20E-04	4.00E-04	2.10E-04	kg N eq
Mineral resource scarcity	2.82E-02	1.49E-02	4.37E-02	2.09E-02	4.02E-02	2.05E-02	kg Cu eq
Ozone formation, Human health	3.50E-02	2.94E-02	4.25E-02	3.14E-02	3.82E-02	2.05E-02	kg NOx eq
Ozone formation, Terrestrial ecosystems	3.64E-02	3.03E-02	4.42E-02	3.24E-02	3.95E-02	2.12E-02	kg NOx eq
Stratospheric ozone depletion	7.62E-06	6.29E-06	1.09E-05	7.42E-06	1.10E-05	5.80E-06	kg CFC11 eq
Terrestrial acidification	6.05E-02	5.43E-02	7.21E-02	5.70E-02	6.84E-02	3.70E-02	kg SO2 eq
Terrestrial ecotoxicity	4.05E+01	3.57E+01	5.99E+01	4.21E+01	5.24E+01	2.79E+01	kg 1,4-DCB
Water consumption	1.53E-01	8.65E-02	1.69E-01	9.24E-02	2.05E-01	1.06E-01	m3
Production cost	8.6	7.9	9.5	8.6	7	4.9	€

2.2 Application of MCDA

In order to incorporate the various environmental as well as the economic criteria, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method of MCDA [9] is used. This is chosen due to its previous application in the context of LCA and because it is one of the most widely applied compensatory methods of MCDA when cardinal indicators are available for all alternatives [10]. This selection is further discussed in section 4.

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All midpoint indicators from LCA and production price of the various polyphenol production methods (Table 1) are used as criteria in the application of TOPSIS.

2.3 Development of Weighting

When applying TOPSIS, there is an inherent application of weighting, even in its default mode, equal weights are applied. This presents a problem because the selection of the ideal alternative is directly related to weighting. Ideally, this process would be completed relative to planetary boundaries [11] using an absolute relationship to impacts from LCA [12]. However, this absolute relationship is not yet well enough understood/developed, nor has it been developed to include all impact categories covered in LCA. As such, an alternative relationship must be established. This poses issues, which are further discussed in section 4.

In this case, normalization factors (NF) [13] are used to derive a relative importance factor (RIF), relating the average value, amongst all of the alternative extraction methods, of each of the midpoint impacts (MI) to the average European's annual environmental impact such that $RIF_i = \overline{MI_i}/NF_i$. The relationship between environmental and other criteria, in this case production cost, is then accounted for such that the sum of all weights is equal to 1000. The resultant weighting is then displayed in tabular form to promote full transparency in the assessment (Table 2, Table 3).

3. Results

After applying RIF, weighting strings can be derived for the application of TOPSIS with a range of importance given to economic impact from 0-1000, of 1000 available points distributed in the weighting profile (Table 2). This is also done for equal weights (EW) amongst environmental impacts and the same range of importance of economic impact (Table 3).

Table 2: Weighting strings including RIF for environmental impacts and a range of importance of economics

product production cost	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0	12.83	276.36	183.72	86.75	58.98	59.26	3.93	28.40	0.61	161.97	0.86	0.004	23.98	28.77	2.05	21.34	42.57	7.62
100	11.55	248.72	165.35	78.08	53.08	53.33	3.53	25.56	0.55	145.78	0.77	0.003	21.58	25.90	1.84	19.21	38.31	6.86
200	10.26	221.09	146.97	69.40	47.18	47.41	3.14	22.72	0.49	129.58	0.69	0.003	19.18	23.02	1.64	17.08	34.06	6.10
300	8.98	193.45	128.60	60.73	41.28	41.48	2.75	19.88	0.42	113.38	0.60	0.002	16.78	20.14	1.43	14.94	29.80	5.34
400	7.70	165.82	110.23	52.05	35.39	35.55	2.36	17.04	0.36	97.18	0.51	0.002	14.39	17.26	1.23	12.81	25.54	4.57
500	6.42	138.18	91.86	43.38	29.49	29.63	1.96	14.20	0.30	80.99	0.43	0.002	11.99	14.39	1.02	10.67	21.28	3.81
600	5.13	110.54	73.49	34.70	23.59	23.70	1.57	11.36	0.24	64.79	0.34	0.001	9.59	11.51	0.82	8.54	17.03	3.05
700	3.85	82.91	55.12	26.03	17.69	17.78	1.18	8.52	0.18	48.59	0.26	0.001	7.19	8.63	0.61	6.40	12.77	2.29
800	2.57	55.27	36.74	17.35	11.80	11.85	0.79	5.68	0.12	32.39	0.17	0.001	4.80	5.75	0.41	4.27	8.51	1.52
900	1.28	27.64	18.37	8.68	5.90	5.93	0.39	2.84	0.06	16.20	0.09	0.000	2.40	2.88	0.20	2.13	4.26	0.76
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table 3: Weighting strings including equal weighting for environmental impacts and a range of importance of economics

product production cost	Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6	55.6
100	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
200	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4	44.4
300	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9
400	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3	33.3
500	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8
600	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2
700	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7
800	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1	11.1
900	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Applying these weightings to the criteria derived from LCA and techno-economic assessment using TOPSIS, it is possible to provide decision support in the form of a single score indicator of idealness of the various technological alternatives (Figure 1).

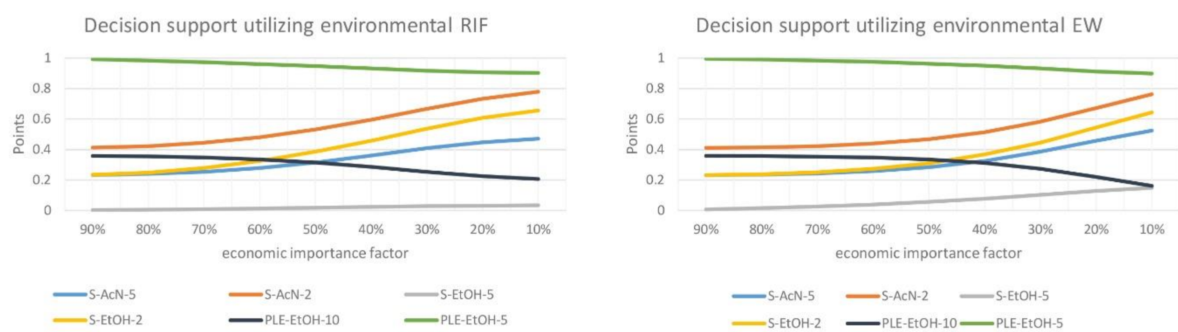

Figure 1: TOPSIS derived single score indicator of idealness (most ideal=1) for both RIF derived environmental weighting and EW environmental weighting amongst a range of EIF

4. Discussion

4.1 Interpretation of results

Based on the application of TOPSIS, it can be easily concluded that the PLE-EtOH-5 method outperforms all other alternative extraction methods. It is both the best economic performer and the best environmental performer in nearly all impact categories. This results in it being classified as the most ideal solution regardless of weighting. In addition, the S-AcN-2 remains the second ranked method regardless of weighting method. This indicates that these two alternatives exhibit characteristics that consistently perform better than the other alternatives. However, once one moves past the top ranked technologies, and must determine a third ranked technology, the picture becomes far less clear. The PLE-EtOH-10, and S-EtOH-2 alternatives vie for the third rank. S-EtOH-2 outperforms PLE-EtOH-10 environmentally,

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while PLE-EtOH-10 outperforms S-EtOH-2 economically. This results in a rank reversal as one changes the weight given to the economic criterion.

As can be seen in Table 4, there is significant range in the importance of specific environmental impacts in RIF for the assessed methods. For example, some impacts such as human non-carcinogenic toxicity, marine eutrophication, and land use are insignificant in relative importance, and mineral resource scarcity is almost entirely irrelevant. On the other hand, fossil resource scarcity and freshwater ecotoxicity make up nearly half of weighting applied to environmental impacts due to the scale of their impact compared to the other environmental criteria relative to the average European's environmental impact.

One other element of note is the difference of decision support between 40% and 70% economic importance factor (EIF) for the EW and RIF weighting. When using RIF, at 60% EIF, S-EtOH-2 and PLE-EtOH-10 are ambiguous in terms of ranking between third and fourth. Around 50% EIF, S-EtOH-2 is unambiguously ranked third when using RIF, however; when using EW, PLE-EtOH-10, S-AcN-5, and S-EtOH-2 are all ambiguous in terms of preference. This rank reversal is due to the difference in weighting for certain environmental impact categories where PLE-EtOH-10 performs similarly to S-AcN-5 and S-EtOH-2. However, despite performing similarly in some environmental categories, when the relationship to environmental importance (Table 4) of the magnitude of emissions is accounted for, the similar environmental performance of PLE-EtOH-10 is discounted in some impact categories, as it is irrelevant in relation to the scale of other environmental impacts. And, S-AcN-5 and S-EtOH-2 outperform PLE-EtOH-10 in fossil resource scarcity and marine ecotoxicity which become exaggerated in terms of influence in the decision support using RIF, relative to the decision support when using EW, due to the relative scale of the impacts in absolute terms. Furthermore, the effective removal of impacts without great relative significance by using RIF allows for greater differentiation between S-AcN-5 and S-EtOH-2, as impact categories where they perform relatively similarly, but are not of great consequence, such as mineral resource scarcity or human non-carcinogenic toxicity, are essentially removed from effecting the decision support.

Table 4: Relative weight of environmental impacts between RIF and EW weighting ($RW = W_{RIF}/W_{EW}$)

Fine particulate matter formation	Fossil resource scarcity	Freshwater ecotoxicity	Freshwater eutrophication	Global warming	Human carcinogenic toxicity	Human non-carcinogenic toxicity	Ionizing radiation	Land use	Marine ecotoxicity	Marine eutrophication	Mineral resource scarcity	Ozone formation, Human health	Ozone formation, Terrestrial ecosystems	Stratospheric ozone depletion	Terrestrial acidification	Terrestrial ecotoxicity	Water consumption
0.2309	4.9745	3.3069	1.5616	1.0616	1.0666	0.0707	0.5112	0.0109	2.9155	0.0154	0.0001	0.4316	0.5179	0.0368	0.3842	0.7663	0.1372

4.2 Alternative weighting methods

Another important element in interpreting the results from RIF weighting is understanding that there is a level of uncertainty in the normalization factors used to derive the RIF, and that the decision to use current emissions as a reference point does not necessarily have a relationship to the severity or consequences of environmental impacts. However, it does provide an indication of the relative importance of an emission, or reduction thereof, to the status quo. If absolute sustainability related factors were available for all relevant impact categories, the application of these instead of normalization factors would be preferable, as they would provide a stronger link to environmental impact.

An alternative to either of these methods would be to derive a RIF weighting from endpoints using e.g. monetization. While this might seem appealing, as there is a stronger connection with environmental damages when using endpoint indicators in LCA, the challenge comes in determining the relative importance of the different damage categories. This relative importance is purely subjective, and as such a specific cultural perspective would be applied to the derivation of the weighting profile. While this could be carried out in a scientific fashion to be representative of a decision maker group, the results would

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already contain some bias toward certain impacts introduced in the endpoint calculation [4, 6]. This would make the results more challenging to interpret and potentially lead to decision support that in the end does not reflect the true preferences of the decision maker.

4.3 Alternative MCDA methods

As discussed in the introduction, there are a number of potential alternatives to the use of MCDA. There are also a number of alternative methods of MCDA (other than TOPSIS) that could have been applied. Methods such as those that include preference comparison based on pairwise comparisons such as analytical hierarchy process (AHP) or outranking approaches such as elimination and choice translating reality (ELECTRE) or preference ranking organization method for enrichment evaluation (PROMETHEE). All of these methods include benefits and drawbacks, however, due to the simplicity of application as well as the easy comprehensibility of TOPSIS, it was chosen for this application. In particular, even when faced with a non-expert audience it is easy to describe how TOPSIS functions, including its relationship to weightings used in its application. This was considered a significant benefit, as it greatly increases the transparency of the application of MCDA and reduces the potential for misgivings when relaying results to non-experts.

5. Conclusions

Based on the results of both economic and environmental assessment, it can be concluded that among the tested extraction methods in the NoAW project, it is likely that the PLE-EtOH-5 alternative will perform best. However, should NoAW be unable to proceed with this technology for upscaling, then S-AcN-2 and S-EtOH-2 and PLE-EtOH-10 are all potential alternatives, depending on the importance given to economic performance versus environmental performance. In addition to the demonstrated ability of MCDA to increase the transparency and reproducibility of a decision making process, it can be concluded that the introduction of RIF as a method of deriving a weighting, relative to equal weights, for use in MCDA for LCA can likely reduce the impact of irrelevant and/or subjective criteria on the conclusions drawn from the application of MCDA that include weighting such as TOPSIS.

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