Valorisation of olive and wine industry co-products techno-economic analysis and life cycle assessment

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ABSTRACT

In this work, a valorisation of olive and wine industry co-products (olive pomace and grape marc, respectively) through different thermochemical processes is studied. First, a characterization of olive pomace and grape marc is made in order to evaluate which thermochemical process is more suitable for each type of biomass. Then a life cycle assessment (LCA) of olive pomace valorisation is made in order to assess the environmental impacts. Several scenarios of biomass conversion process were considered: combustion, gasification and hydrothermal carbonization (HTC) followed by gasification to generate electricity; and pyrolysis to produce biochar, bio-oil and syngas. Finally, a techno-economic analysis was performed for each mentioned scenario in order to evaluate the feasibility and conclude which scenario is more economically advantageous. Results suggest that valorisation of olive pomace might be more suitable through the gasification process and grape marc through the pyrolysis process. From the LCA was possible to conclude that combustion scenario has the biggest environmental impact. In comparison, gasification, HTC and pyrolysis presented a lower impact with a value of 69.45%, 50.96% and 40.97% respectively, considering combustion as 100% impact. Regarding the techno-economic analysis, several scenarios have promising results with some scenarios with payback periods inferior to 5 years. The only exception is HTC followed by gasification which in current days is not competitive with other technologies. Overall gasification and pyrolysis are better alternatives to the valorisation of olive pomace and grape marc. Also drying has an important role in terms of environmental impact and economic viability.

Keywords: Grape marc, Olive Pomace; Thermochemical Processes; LCA; Techno-Economic Analysis

1. Introduction

Over the last decades energy consumption had an abrupt increase. This trend will continue as ensuring everyone has sufficient access to energy is an ongoing and pressing challenge for global development [1]. Our energy systems have important impacts, as more than 80 % of the world's energy comes from fossil fuels. In order to meet our global climate targets and avoid dangerous climate change, the world needs a significant and concerted transition from an energy system dominated by fossil fuels to a low carbon one dominated by renewable energies [2]. Bioenergy accounts for 70% of the renewable energy consumption and one of the most promising sectors for growth in the bioenergy is the agriculture sector. Currently, the sector contributes less than 3% to the total bioenergy production but its potential is estimated that could meet about 3-14% of the total energy supply globally [1,3].

In Portugal there is a high abundance of agricultural land and production. The country has two agricultural industries that have huge potential in terms of biomass residues which are the wine and olive industry [4]. Wine has a production of over 6 million hectolitres per year and the production of around 179 thousand tonnes of solid waste and 1.34 million tonnes of wine wastewater [5]. Olive oil industry produce around 800 thousand tonnes of olives annually which produce around 1.25 million tonnes of solid waste and 374 thousand tonnes of olive mill wastewater [6].

The main solid residue coming from the wine making process is grape marc. Grape marc consists of grape skin, stalks, seeds and moisture collected after grape juiced extraction (pressing). It is characterized by high organic content, low nitrogen and phosphorus concentrations and its rich in carbohydrates and phenolic compounds [7,8]. In Portugal grape marc is used to produced distillate beverages, use for composting or animal feeding [9]. On the other hand, olive pomace is constituted of crushed olive stones, together with vegetation water, process water and all materials coming from the fruit except the olive oil, which represents the main residues of the olive oil extraction process by weight, 450-800 kg for each tonne of olive processed. The corresponding pomaces are usually referred as two- or three phase olive pomaces (2POP and 3POP respectively), with the amount of water being the main difference[10,11]. In Portugal currently pomace (2POP) is used to recover residual olive oil, which is estimated at 2% of the pomace weight. This process consists of drying and solid liquid extraction with hexane. After oil extraction, the exhausted solid obtained is called exhausted olive pomace (EOP) accounting for 18-25% of the pomace dry weight and it is used as biomass to recover energy [9,10]. One alternative to the current uses of grape marc and olive pomace could be turning into thermochemical conversion technologies that could be a solution to the deficit of forest biomass that Portugal is currently facing [4]. Direct combustion is still the mostly used thermochemical process for bioenergy pathway worldwide. Complete combustion involves the production of heat as a result of the oxidant of carbon-and hydrogen rich biomass to CO_2 and H_2O [12]. Nevertheless, there are other pathways for conversion of biomass such as gasification, HTC and pyrolysis. Gasification is the partial oxidation of biomass fuel at high temperatures (typically in the range of 800-1000 ºC) to form a low caloric value combustible mixture together with char and ash. The produced gas is called syngas and it is composed by CO, H_2, CH_4, CO_2, H_2O, N_2 and other hydrocarbon such as C_2H_4 and C_2H_6. The other substances produced apart from the gas are ash, coal particles, tar and oils. Syngas can be combusted to generate heat or electricity (via shaft work in a gas turbine or internal combustion gas engine) or refined to produce hydrogen gas or liquid transport fuels via Ficher-Tropsch synthesis [7,13]. HTC is a process that involves low temperature heating of the raw biomass to achieve a more energy dense, hydrophobic product. Heating takes place in a water suspension at saturated pressures, making the process well suited to high moisture biomass such as grape marc and olive pomace. HTC is an exothermic process that lowers the O:C and H:C ratios of the biomass to increase the heating value. In the case of HTC, this is achieved via the following successive reaction mechanisms: hydrolysis, decarboxylation, dehydration, aromatization and recondensation [7]. Pyrolysis is the thermal decomposition of biomass fuel in the absence of oxygen at temperatures of around 400-700 ºC; the process is endothermic. These thermochemical biomass conversion process produces a mix of gas, liquid (tar or bio-oil) and solid (char) products depending on the pyrolysis conditions applied. Pyrolysis is differentiated between slow pyrolysis, with residence times ranging from minutes to days and optimized for the production of char whereas fast pyrolysis, with residence times on the order of seconds or minutes, it is optimized for the production of bio-oil [7,12].

In order to assess and compare different processes of valorisation of residual biomass it is possible to use different approaches and criterias. Two possible approaches that gives us important insights is the LCA approach and techno-economic analysis. LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to which lead to environmental improvements [14]. Techno-economic assessment is a cost benefit comparison using different methods. It intends to evaluate the likelihood of different technology scales and applications; evaluate the economic feasibility of a specific project; investigate cash flows over the lifetime; and also to compare the economic quality of different technology applications providing the same service. Using this type of analysis is possible to make a sustained decision about a project [15].

In the literature were found some relevant studies regarding LCA of grape marc and olive pomace through different thermochemical processes. Benetto et al [16] results showed that the production of pellets from grape marc for heat production purposes is a promising technology from an environmental perspective, which is always superior to alternative fuels at endpoint impact levels. Durman et al [17] concluded that composting the olive pomace has very high impact score compared to other scenarios, mainly because of raw materials used and hazardous chemical emitted in the process. On the contrary, Cossu et al [18] stated that composting was of 2 to 4 orders of magnitude less impacting than domestic heating and power generation. Regarding gasification, Parascanu et al [19] reached to the conclusion that gasification scenario exhibited higher impact values at mid points level, than the combustion scenario. The results indicate that combustion process is two times more efficient than the gasification process for electricity generation. Nevertheless, this is against several studies which showed that gasification performance of olive pomace is comparable to combustion [13,20]. Concerning HTC, Benavente et al [21] stated that in comparison with current management approaches alternatives using HTC is more environmental advantageous than composting and anaerobic digestion, but the use of HTC is not as environmentally advantageous as incineration with energy recovery. More recently, Mendecka et al [22] concluded that the environmental performance of HTC is mainly dependent on its energy consumption. Concerning pyrolysis Parascanu et al [23] showed that the main affecting factors for all impact categories are related to the consumption of energy required to perform biomass conversion. Also, El Hanadeh et al [24] concluded that energy utilization of fast pyrolysis products reduces more the GHG emissions than slow pyrolysis and using the biochar as soil amendment.

Regarding a techno-economic analysis Zhang et al [25] found pyrolysis to be superior method of utilizing grape marc from both economic and environmental perspectives in comparison to combustion. Two works focusing on gasification were found. Borello et al [13] presented a thermodynamic model of CHP plant with an electric efficiency of 25% and with a 30% thermal efficiency. In terms of profitability cogeneration model had better results compared to case studies with just electricity demand. The other work performed by Hermoso-Orzáez et al [20] which the results demonstrate the applied technical and economic feasibility of thermal gasification, for the production of LHV syngas with highest power energy (more than 5 MJ/m^3) produced in mixtures of 100% to 80% of olive pomace with overall electric efficiencies close to 30%. This study was complemented with economic-financial analysis. All the mixtures had a payback period inferior to 10 years. Finally, an HTC process was designed by Lucian & Flori [26]. The overall plant efficiency was 78%. The production cost of pelletized hydrochar and its break-even point were determined to be 157 €/tonne and 200 €/tonne, respectively. The authors concluded that such values make the use of hydrochar as a CO_2 neutral biofuel attractive.

The works mentioned focus solely on one or two thermochemical processes for the valorisation of grape marc or olive pomace and sometimes compare them other waste valorisation methods. The innovation of these work is that is going to evaluate environmentally and economically four different thermochemical processes (combustion, gasification, HTC followed by gasification and pyrolysis) for the valorisation of olive pomace at the same time.

Therefore, a characterization of olive pomace and grape marc is made in order to evaluate which thermochemical process is more suitable for each type of biomass. Then a LCA of olive pomace valorisation is made in order to assess the environmental impacts. Several scenarios of biomass conversion process were considered: combustion, gasification and HTC followed by gasification to generate electricity; and pyrolysis to produce biochar, bio-oil and syngas. Finally, a techno-economic analysis was performed for each mentioned scenario in order to evaluate the feasibility and to conclude which scenario is more economically advantageous. In the end, the objective is to identify which process is the more suitable alternative for grape marc and olive pomace

2. Materials and Methods

2.1. *Feedstock characterization*

The performance of different thermochemical conversion pathways relies on the use of appropriate biomass feedstocks. The sample used in this work will be grape marc and olive pomace based on empirical data. All the studies mentioned on the literature review and with relevant data regarding grape marc and olive pomace were considered and data was collected. The data selected included biomass calorific value, ultimate analysis and proximate analysis.

Data was categorized in the next sections, to evaluate if it is possible to see differences between the different types of biomasses. To better understand the results, it was applied the mean and standard deviation. With the mean is possible to know which is the average value of a certain characteristic and with the standard deviation to assess how scattered the values are. The formulas used are represented below:

$$\text{Mean: } \bar{X} = \frac{\sum X}{N} \quad (1)$$

$$\text{Standard deviation: } \sigma = \sqrt{\frac{\sum (X-\bar{X})^2}{N-1}} \quad (2)$$

The expected value of each category will be defined as:

$$\text{EV} = \bar{\text{X}} \pm \sigma \quad (3)$$

The range will be defined as:

$$\text{Range: } (\text{Min}(\text{X}); \text{Max}(\text{X})) \quad (4)$$

The expected value will be a way of predicting more closely which value should be expected to find in each type of biomass and category, and the range to state which spectrum of values where found in the literature.

The samples were categorized in three categories: grape marc (GM), olive pomace and EOP. Where EOP is olive pomace dried and without the residual oil after a hexane extraction.

2.2. *LCA Mehodology- Olive pomace Valorisation*

In this work, the LCA was carried out using the software SimaPro and it is applied by using general methodological framework and standards for LCA defined by ISO 10040 and ISO 14044 [23]. All the data used was based on empirical works or in justified assumptions.

The aim of this study is to compare olive pomace valorisation through four different thermochemical processes (combustion, gasification, HTC followed by gasification and pyrolysis) in terms of environmental performance. In this regard an LCA methodology is used to identify the environmental impact associated with each studied thermochemical conversion process. The LCA was carried out in accordance with gate-to-cradle approach, taking in account just the moment olive pomace enters in facility and its valorisation. Downstream processes, such as olive production, olive oil extraction and the possible transport of olive pomace are not considered in this study because it is assumed that these values are the same for all management alternatives. The functional unit of this study is defined as 1 kg of 2POP (extraction method used in Portugal) with 60% moisture.

In total there were seven scenarios modelled, which are schematically represented in Figure 1-4. Each Figure 1-3 represent two scenarios, one where the hot exhausted gases from the thermochemical process are recovered for the drying process (heat recovery system) and other where the drying process is dependent on the use of natural gas.

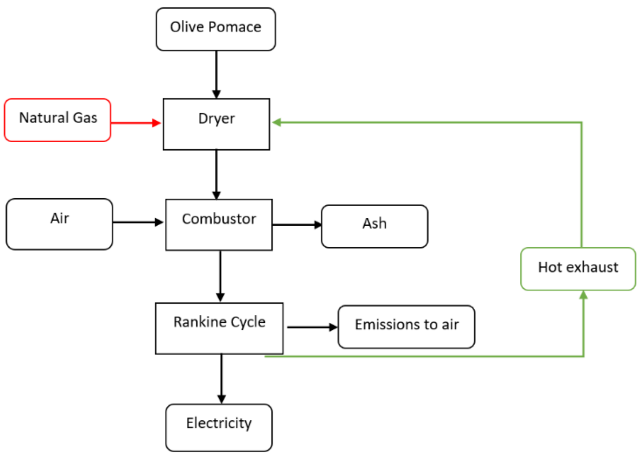

Figure 1- Combustion scenarios C.A (red) and C.B (green)

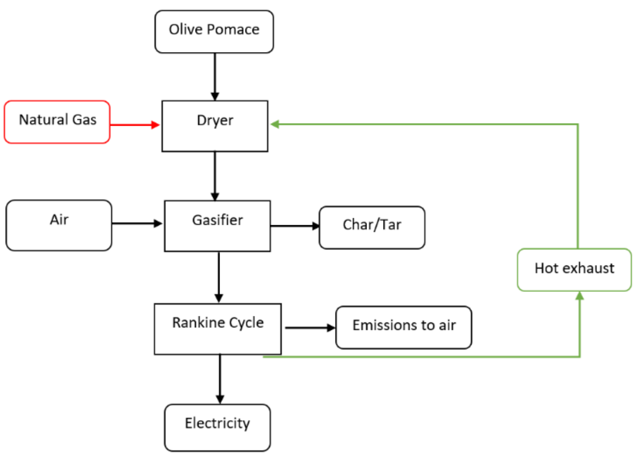

Figure 2- Gasification scenarios G.A (red) and G.B (green)

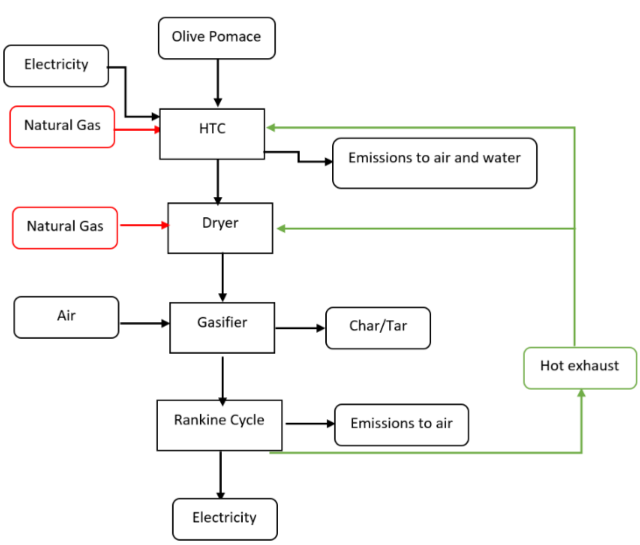

Figure 3- HTC followed by gasification scenarios HTC.A (red) HTC.B 6 (green)

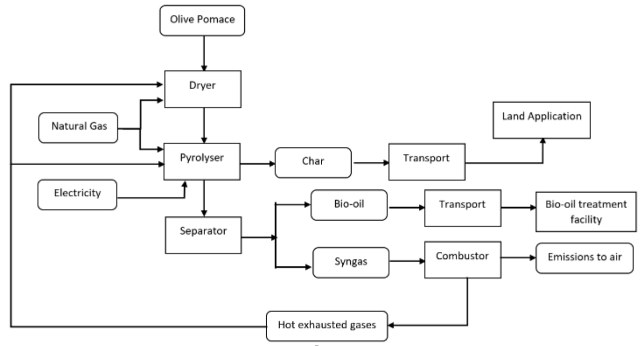

Figure 4- Pyrolysis scenario P.A

To perform the environmental assessment, a data collection from the inputs and products related to the analysed processes is required. The Life Cycle Inventory is the compilation and quantification phase of all flows (raw materials, energy and other goods and services, emissions, waste and products) related to the production system during its entire life cycle (ISO4040, 2006 and ISO14041, 1998) [27] .The inventory data associated with the scenarios mentioned before were either collected from previously published data sources, including life cycle inventory studies, scientific literature describing experimental studies, and/or Ecoinvent data bases.

Finally, due to the advantages and disadvantages of the mid-point and end-point indicators, both methodologies have been combined in this study. In this way, on the one hand, decisions can be made using mid-point indicators, which are more certain but, in some cases, may have less relevance for decision support. On the other hand, end-point indicators are used, which have been shown to be more relevant and decisions can be made more easily but have less certainty [19].

Nine mid-point impacts were screened for all scenarios: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), natural land and fossil depletion (FD) [19].

In addition, for a better understanding, the final point indicators were addressed. The following end-point impacts were examined: damage to human health (HH), damage to ecosystem diversity (ED) and damage to resource availability (RA).

Finally, all the results were normalised, which facilitates the comparison between impact scores of different impact categories. Using the normalisation value, it is possible to identify easily and faster the impact categories with highest and lowest contributions that affect the environment, simplifying the final decision making. As defined in ISO 14044, the normalisation is a process to calculate the magnitude of the results of impact category indicators, in relation to a certain reference information. In this case, the results for each category are normalised with respect to average European emissions [19].

2.3. *Techno-Economic analysis*

This chapter is focused on comparing the same four different thermochemical conversion methods but through a techno-economic analysis in order to assess the feasibility of a project regarding valorisation of olive pomace. For this assessment the scenarios considered were the same of the LCA analysis. Four plants will be considered, three of them designed to generate electricity through combustion, gasification and HTC followed by gasification; one of them designed to produce biochar, bio-oil and syngas through pyrolysis. All the facilities receive olive pomace with 60% moisture and it is assumed that all the stages of the process (Figure 1,2,3,4) occur on site. Since the ultimate goal is to compare technologies, the results were normalized considering an input of 1 kg/h of olive pomace, but all the data is based on facilities with large capacity of more than 1 ton/h.

Capacity factor is defined as the ratio between the energy generated in a period and the total energy that could be generated if the facility runs at maximum output during the same period and without interruption [28]. Therefore, if the factory works without stoppage 24 hours every single day of the year the capacity factor would be 100%. In this work it was assumed for all plants a capacity factor between 60 to 85%.

Another important factor is the lifetime of the plants. Literature reports values between 15 to 25 years, being the majority of the values reported equal or superior to 20 years [29]. Consequently, it is going to be assumed a lifetime of 20 years for all the biomass plants.

In terms of cost structure, the approach used here is a simplified one. This allows greater scrutiny of the underlying data and assumptions, improved transparency and confidence in the analysis, as well as facilitating the comparison of costs for different technologies in order to identify what are key drivers in any differences. The costs considered were:

- Feedstock cost- Price of olive pomace which was considered 15 €/ ton.
- CAPEX- Which include all the costs necessary to perform the project [29].
- Operation and maintenance expenditure (OPEX)- Which refers to the costs associated with the operation of biomass plant [29].
- Other costs- This will be the cost associated with ash handling, natural gas and electricity consumption [29].

In terms of revenues, the plants that generate electricity (combustion, gasification and HTC followed by gasification scenarios) generate revenue by selling the electricity produced. The pyrolysis plant generates revenues by selling biochar and bio-oil. In this part of the study it is taken into account the cost of treatment of bio-oil (in the LCA was not taken into account).

The economic-financial analysis for the four installations studied was made based on net present value (NPV), evaluation of the period of return on investment (payback period) (PBP) and the internal rate of return (IRR). The evaluation will be done for entire lifetime of the project (20 years), N=20.

To perform the analysis of the seven scenarios previous explained in section 2.2, it was considered a worst-case, an average and a best-case scenario for each one of them. Consequently, the total number of scenarios considered was 21. The range of values used for this analysis is detailed on Table 1, in certain cases it is detailed for the type of biomass plant, in other cases where the values is not detailed for a certain plant, the value applies for all scenarios.

Table 1- Data for all scenario in techno-economic-analysis

Cost Structure	Description	Worst scenario	Average scenario	Best scenario
Feedstock price				
	Olive pomace cost (€/ton)	15	15	15
CAPEX				
	Combustion plant (€/KW)	3780	2646	1512
	Gasification Plant (€/KW)	4872	3360	1848
	HTC Plant (€/(kg/h))	709.52	709.52	709.52
	Pyrolysis Plant (€/ (dry kg/h))	2594.29	1973.25	1324.80
	Bio-oil treatment facility	39	39	39
OPEX				
Fixed	Combustion plant (% Investment Cost)	4.2	3.7	3.2
	Gasification plant (% Investment Cost)	5	4	3
Variable	Combustion plant (€/KWh)	0.0039	0.0036	0.0032
	Gasification plant (€/KWh)	0.0031	0.0031	0.0031
Fixed and variable	HTC Plant (€/kg)	0.0416	0.0333	0.0250
	Pyrolysis Plant (%Investment Cost)	5	4.5	4
Other Costs				
Ash handling	Price (€/kg)	0.1109	0.1109	0.1109
Natural gas	Price (€/KWh)	0.0609	0.0590	0.0571
Electricity	Price (€/KWh)	0.1485	0.1435	0.1385
Revenues				
Capacity factor	All plants (%)	60	72.5	80
Electric efficiency	Combustion plant (%)	25	30	35
	Gasification plant (%)	17	25	33
	HTC followed by gasification plant (%)	16	24	32
Electricity	Selling price ((€/KWh)	0.1020	0.1055	0.1090
Biochar	Selling price (€/kg)	0.084	0.168	0.210
Bio-oil	Selling price (€/kg)	0.269	0.391	0.330

3. Results and discussion

3.1. *Grape Marc and Olive Pomace Characterization*

Table 2 and 3 displays the calorific values, proximate analysis and ultimate analysis of different samples of grape marc and olive pomace. From the tables mentioned each category has an expected value and a range, with the expected value it is possible to predict a priori which values are more likely to be obtain for each type of sample. The range represents the spectrum of values stated in the literature.

Table 2- Calorific value and proximate analysis of GM and OP

Sample	Result	Calorific value (MJ/kg)		Proximate analysis (%)				N
		HHV	LHV	Moisture $_{wb}$	FC^{db}	VM^{db}	Ash^{db}	
GM	EV	20.57±0.98	19.42±0.73	-	24.80±3.58	67.58±4.79	6.78±2.85	20
	Range	19.50-21.80	18.02-20.20	60.00-75.00	17.29-31.10	55.60-75.49	2.18-13.30	
OP	EV	21.15±2.15	20.75±0.49	-	16.39±4.84	77.95±3.92	4.45±2.42	8
	Range	16.70-22.70	20.40-21.10	40.00-70.00	11.04-24.20	72.00-81.75	2.30-7.77	
EOP	EV	19.58±1.45	18.30	-	18.95±3.44	66.69±4.55	7.35±2.77	6
	Range	17.10-20.70	-	-	13.70-22.15	60.83-73.50	4.40-10.37	

Table 3- Ultimate analysis of different samples of GM and OP

Sample	Result	Calorific value (MJ/kg)		Proximate analysis (%)				N
		HHV	LHV	Moisture $_{wb}$	FC^{db}	VM^{db}	Ash^{db}	
GM	EV	20.57±0.98	19.42±0.73	-	24.80±3.58	67.58±4.79	6.78±2.85	20
	Range	19.50-21.80	18.02-20.20	60.00-75.00	17.29-31.10	55.60-75.49	2.18-13.30	
OP	EV	21.15±2.15	20.75±0.49	-	16.39±4.84	77.95±3.92	4.45±2.42	8
	Range	16.70-22.70	20.40-21.10	40.00-70.00	11.04-24.20	72.00-81.75	2.30-7.77	
EOP	EV	19.58±1.45	18.30	-	18.95±3.44	66.69±4.55	7.35±2.77	6
	Range	17.10-20.70	-	-	13.70-22.15	60.83-73.50	4.40-10.37	
	Range	16.70-22.70	18.30-21.10	-	11.04-24.20	60.83-81.75	2.30-10.37	

Regarding olive by-products, comparing olive pomace and EOP were found relevant differences. These differences were attributed to the stage of hexane extraction in the EOP, which by removing the residual oil, decreased the volatile matter (VM) content, as it is possible to see in Table 2 where the difference in VM content between olive pomace and EOP is more than 10%. This reduction in VM in terms of percentage resulted in an increase of fixed carbon (FC) and ash in EOP compared to olive pomace. Moreover, it was expected to obtain a lower C and H content in EOP which was very slight (H remain constant), since fatty acids in the oils are mostly composed of C and H. Finally, these observations were consistent with a lower calorific value for EOP (19.58 MJ/kg) as compared to olive pomace (21.15 MJ/kg). Comparing grape marc and olive pomace these two by-products are much more similar than initially expected. Calorific value in both biomass is close to 20 MJ/kg and initial moistures quite high which require a drying process. Excluding the EOP the VM in the olive pomace is around 10% higher than in the grape marc samples, consequently apparently olive pomace should be more appropriate to be gasified. On the other hand, FC and ash content of grape marc are around 7-8% and 2% respectively higher than olive pomace which indicates that grape marc might be more fit to HTC pre-treatment (which is expected to reduce ash content and obtain high char yields) or recovery via pyrolysis. In terms of ultimate analysis, they are quite similar, the major differences are in the C and O content which is around 3% higher and 3% lower respectively in the case of olive pomace compared to grape marc.

Concluding, besides slight differences in general they are comparable types of biomass, that is why on the further section for an LCA and Techno-Economic approach it was just considered an olive pomace sample.

3.2. *Life Cycle Impact Assessment*

LCA results for each evaluated impact category associated with the scenario considered are reported in this section. A positive impact potential indicates a burden to the environment (negative environmental effect), while a negative potential indicates environmental emissions savings (positive environmental effect).

In this section a comparison between the different thermochemical processes is going to be made. A mid-point and end-point analysis will be used. Figure 5 and 6 show the results obtained for the different thermochemical processes

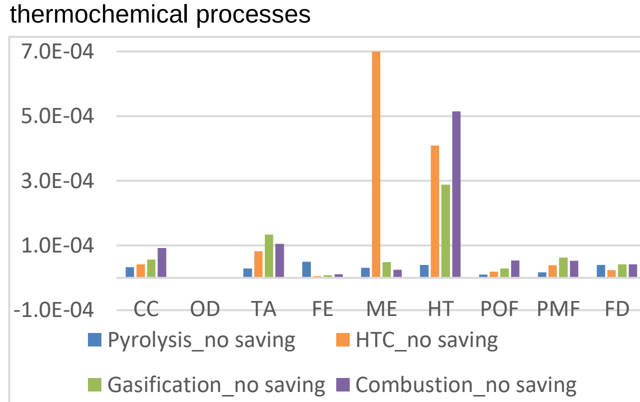

Figure 5- Comparison between different thermochemical processes using a mid-point analysis

The mid-point analysis focus on unique environmental problems. Consequently, this method does not provide any information on damage information but allows to understand which scenario has bigger impact on each

category.
Figure 5 highlights the results obtain using the mid-point analysis. Combustion has the major impact on four categories which are: climate change due to a higher emissions of GHG; human toxicity due to a higher emissions of dichlorobenzene equivalents; photochemical oxidant formation caused by a higher emission of non-methane volatile organic compounds; and fossil depletion due to higher use of fossil fuels. Then gasification leads in two categories: terrestrial acidification related to higher transformation of air pollutants (SO_2) into acids which cause a higher acidification of soils; and particulate matter formation which is given in PM_{10} equivalents. Furthermore, HTC scenario has a higher contribution in one category which is marine eutrophication, cause by high emissions of nitrate equivalents into water. Finally pyrolysis has the major impact in two categories: ozone depletion caused by emissions of CFC and NO_x which are quite low and that's why this value is the lower one compared to all categories; and freshwater eutrophication caused by the emissions of phosphate equivalents.

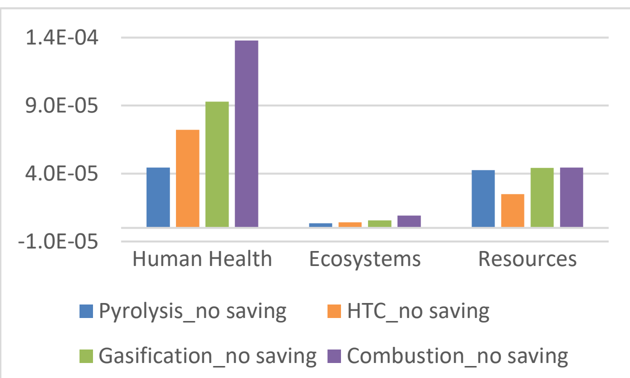

Figure 6- Comparison between different thermochemical processes using an end-point analysis

The conversion of mid-point into end-point impacts simplifies the interpretation of the LCA results and simplifies the comparison between scenarios. Therefore, from Figure 6 is possible to make a direct comparison between the different thermochemical processes impacts. Regarding human health and ecosystems, the trend is similar from the higher to the lowest impact the order is: combustion, gasification, HTC followed by gasification and pyrolysis. Regarding resources all have similar impacts with the exception of HTC which is around 40% lower. Consequently, the overall impact from the highest to the lowest is: combustion, gasification, HTC followed by gasification and pyrolysis. Based on the single score impacts, considering combustion as 100% impact the comparative value of gasification, HTC and pyrolysis are 69.45%, 50.96% and 40.97% respectively. Also drying had a relevant impact and a scenario with heat recovery would reduce the overall impact of combustion, gasification and HTC followed by gasification by 25.42%, 36.70% and 28.18% respectively.
Concluding this section, from an environmental point of view pyrolysis presented the best results being its impact 60% lower than the combustion scenario. Gasification and HTC followed by gasification also had promising results with 30% and 50% lower impact compared to combustion.

3.3. *Techno-Economic Analysis Discussion*

Based on the economic model presented on section 2.3 the results obtained for each scenario are presented on Table 4. Also, all the scenarios which have a negative cash flow and/or NPV negative (N=20) will be considered unviable.

Table 4- Economic model results

Plant type	Scenario	Cash flow	NPV (N=20)	PBP	IRR (%)
Combustion	S1	-61.96	-	-	-
	S2	101.64	-1295.62	-	-
	S3	321.98	1727.901	7	20.1
	S4	169.93	-1043.59	-	-
	S5	373.1	1471.78	9	15
	S6	629.99	4867.91	3	40.4
Gasification	S7	-179.95	-	-	-
	S8	3.51	-2431.72	-	-
	S9	280.77	1070.90	10	14.6
	S10	51.94	-1903.46	-	-
	S11	274.97	335.676	16	9.2
	S12	588.78	4210.91	4	32.7
HTC followed by gasification	S13	-305.53	-	-	-
	S14	-104.68	-	-	-
	S15	180.24	-609.19	-	-
	S16	-174.83	-	-	-
	S17	48.32	-2585.72	-	-
	S18	353.85	1160.68	11	13.2
Pyrolysis	S19	-0.82	-	-	-
	S20	206.33	486.01	13	11.2
	S21	412.59	3120.24	4	37.9

In general terms 9 scenarios had positive results. Beginning with a distinction between worst, average and best-case scenarios it is possible to make the following conclusions. All the worst-case scenarios have negative cash flows and/or negative NPV which is expected since the worst estimative were used in every parameter. Regarding the average scenarios it was obtained 3 positive results; combustion with heat recovery, gasification with heat recovery and pyrolysis; the PBP was 9, 16 and 13 years; and the IRR 15, 9.2 and 11.2 % respectively which suggests that combustion plant have superior performance, to pyrolysis and gasification plants. Finally, all the best-case scenarios had positive results with the exception of HTC followed by gasification with no heat recovery.

Comparing technologies, combustion presented the best results with 3 positive results (S3, S5 and S6) all with payback periods inferior to 10 years and IRR superior to 15. It was also obtained the higher value of NPV, lower PBP and higher IRR from all the scenarios with a value of 4867.91, 3 years and 40.4% for S6 respectively. Gasification had similar results to combustion with 3 positive results but with superior payback periods and lower IRR and NPV. This difference to combustion is mostly caused by a lower amount of revenues in gasification scenarios which results in a lower cash flow. Nevertheless, S12 had the second highest NPV and second lowest PBP with a value of 4210.91 and 4 year respectively. Then HTC followed by gasification presented the worst results with just one positive scenario (S8), as a result of having a higher CAPEX and annual overall cost and a lower revenue generation. Regarding pyrolysis it has 2 positive scenarios from 3, relatively to the best-case scenario (S21), it has the second highest IRR and second lowest PBP with a value of 37.9% and 4 years.

Overall, the results show that as expected, the scenarios with heat recovery have better results that the ones without, which indicates that the drying cost is a major factor for the operating plants with this type of biomass with high moisture. In addition, pyrolysis looks competitive with the systems with heat recovery. Also, that combustion presented the best results in terms of economic analysis, probably due to the fact that more than 90% biomass plants are combustion ones [29], which means it is a more developed technology with higher efficiencies and lower costs associated. HTC followed by gasification is not competitive with the other technologies and does not seem a viable solution to the present days. In the future with a reduction of HTC costs and a higher HTC performance (higher energy yield, lower moisture after HTC and better hydrochar properties) this combination of processes may be a competitive solution economically.

To conclude based on the current data combustion, gasification and pyrolysis plant seem viable project for valorisation of olive pomace and grape marc (which as similar properties as seen in section 3.1). The major problem is the drying process which can be solved by using a heat recovery solution. Another possible solution is instead of using olive pomace as input is using EOP, which is already dried and has no current usage after the extraction of the residual oil. Finally, HTC followed by gasification does not seem a viable solution for the valorisation of this type biomass in current days.

3.4. *LCA and Techno-Economic analysis*

In section 3.2 and 3.3 were discussed the results obtained of the LCA and techno-economic analysis independently. In this section both results will be assessed in order to evaluate which scenario(s) have best results in terms of conciliating environmental impact and economic results.

From section 3.2 it was possible to conclude that combustion have the higher environmental impact being pyrolysis the scenario which presented the best results with an overall impact 60% lower. Also, gasification and HTC prior to gasification had promising results with an overall impact 30 and 50% lower than combustion. Regarding the scenarios with heat or no heat recovery, the drying process has a significant environmental impact and using a system with system recovery could reduce the overall impact by 25.42-36.70%.

From section 3.3 it was possible to conclude that economically combustion presented the best results. Nevertheless, gasification and pyrolysis also presented promising results. On the other hand, HTC is not competitive in the current days. Concerning the drying process, drying had a major impact on the overall costs and if it is just considered the scenarios without heat recovery pyrolysis scenario presented the best results.

As a result of the stated above, combustion and HTC followed by gasification are worst alternatives for the valorisation of olive pomace, the first due to the fact that has around two times higher environmental impacts than the other scenarios and the second because it is not an economically viable. On the other hand, gasification and pyrolysis seem better alternatives with environmental impacts around 30-56% and 60% respectively lower than combustion and also with payback period of an investment of 4 years for the best-case scenario. Another important conclusion is that due to high moisture of this type of biomass drying has an important role in terms of environmental impact and economic viability.

4. Conclusion

This work focuses on the valorisation of olive and wine industry co-products (olive pomace and grape marc respectively) through different thermochemical processes. These two industries produce more than 1.4 million tonnes of solid waste per year in Portugal which must be handled.

From the characterization of olive pomace and grape marc was found that these two by-products were very similar. Calorific value in both biomass is close to 20 MJ/kg and initial moistures quite high (40-75%) which require a drying process. VM of olive pomace is around 10% higher than in the grape marc samples, consequently apparently olive pomace should be more appropriate to be gasified. On the other hand, FC and ash content of grape marc are around 7-8% and 2% respectively higher than olive pomace which indicates that GM might be more suitable to an HTC pre-treatment (which is expected to reduce ash content and obtain high char yields) or recovery via pyrolysis. In terms of ultimate analysis, they are quite similar, the major differences are in the C and O content which is around 3% higher and 3% lower respectively in the case of olive pomace compared to grape marc. Both samples of biomass are very comparable and probably could be valorised in the same type of facility and for that reason the LCA and techno-economic analysis was only made based on the literature of olive pomace sample.

Subsequently, from life cycle impact assessment was possible to conclude that the overall impact of combustion was the highest of all and if combustion was considered as 100% impact the comparative value of gasification, HTC and pyrolysis were 69.45%, 50.96% and 40.97% respectively. Finally drying had a relevant impact and a scenario with heat recovery would reduce the overall impact of combustion, gasification and HTC followed by gasification by 25.42%, 36.70% and 28.18% respectively. In regard to the techno-economic analysis, combustion plant presented the best results with payback as short as 3 years. Gasification (with heat recovery) and pyrolysis plant also presented promising results with payback period inferior to 4 years to the best case-scenario. On the other hand, HTC followed by gasification it is not competitive with the other technologies in the current days due to higher initial investment cost and also to due to a higher operational cost associated. Also was possible to conclude that the scenarios with heat recovery have better results that the ones without, which indicates that the drying cost is a major factor for the operating plants with this type of biomass with high moisture. In addition, pyrolysis looks competitive with the systems with heat recovery.

Finally, joining the LCA and techno economic analysis was possible to state that gasification and pyrolysis plant are better alternatives to the valorisation of olive pomace compared to combustion which has a higher environmental impact and HTC prior to gasification which is not economically viable. Another important conclusion is that due to high moisture of this type of biomass drying has an important role in terms of environmental impact and economic viability. Therefore, two possible solutions, could be using a system of heat recovery which reduces significantly thermal input needed or instead of using olive pomace, using EOP which is already dried.

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