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Techno-economic and profitability analysis of food waste biorefineries at European level

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Abstract

Food waste represents a potential source to produce value-added materials replacing the use of virgin ones. However, the use of food waste as feedstock in biorefineries is still at an early stage of development and studies assessing its economic viability at large scale are lacking in the literature. This paper presents a techno-economic and profitability analysis of four food waste biorefineries that use wastes from tomato, potato, orange, and olive processing as feedstock. The study includes the assessment of potentially available quantity of those waste flows in Europe. Due to the low technology readiness level of this kind of biorefineries, a screening methodology to estimate the investment and manufacturing costs as well as two profitability ratios (the return on investment and the payback time) was adopted. Results show that not all the waste feedstock have the same potential and that the most profitable options are those related to implementing fewer plants, namely concentrating the production and capitalising on economies of scale.

Keywords: Food waste; biorefinery; profitability; techno-economic assessment; bioeconomy; circular economy

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1. Introduction

Food waste (FW) is a major economic, social and environmental concern and strategies towards its reduction are being developed both at global and European levels. The United Nations has defined the Sustainable Development Goal 12, which targets include: "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" (UN, 2015). Besides having committed to achieve this goal, the European Commission has defined FW as one of the priority areas of the European circular economy action plan (EC, 2015). The use of FW in biorefineries is foreseen as a potential strategy to contribute to the achievement of the required targets and, simultaneously, to reduce the use of both fossil and bio-based resources, supporting the transition to a circular bio-economy (Dahiya et al., 2018) at lower virgin material intensity.

FW is generated along the whole Food Supply Chain (FSC) and particularly, in the consumption stage (56%) and in the food manufacturing stage (around 38%) (Monier et al., 2010). Contrary to the FW generated at the consumption stage, which composition presents high level of heterogeneity, FW generated in the food processing stage presents high compositional homogeneity. Therefore, it has high potential to be used for the extraction of high-value products. However, this FW is in some cases diverted to landfill with the subsequent economic and environmental impact, or in the best case, utilized to produce animal feed or in processes to recover energy (e.g. anaerobic digestion). This loss or underutilization of functionalities can be avoided using it as feedstock in biorefineries focused on value-added products (Ong et al., 2017) and chemicals (Matharu et al., 2016).

The concept of biorefinery refers to facilities that integrate different conversion processes to produce different products such as fuels, heat, power, and value-added chemicals using biomass as feedstock (Cherubini et al., 2010). Nizami et al. (2017) reviewed different types of waste biorefinery concepts and highlighted that most of them are primarily based on single conversion processes to produce distinctive fuels and chemicals. Most of the biorefineries proposed in the literature are focused on the production of bioenergy or biofuels (Pommeret et al., 2017), mainly due to the high price of crude oil in the market, and each biorefinery can produce a specific fuel depending on the type and availability of feedstock (Mohan et al., 2016). For example, Yang et al. (2014) studied a biorefinery process where the starch residue from instant noodle waste is converted to bioethanol with simultaneous saccharification and fermentation. FW-to-energy conversion technologies usually present high Technology Readiness Levels (TRL) and some of them are even at the commercial scale such as anaerobic digestion (Ren et al., 2018), being the cost estimation of the new biorefinery concept relatively easier since real costs are available for the escalation and the validation of the results.

On the other hand, biorefineries focused on value-added products and chemicals present a low TRL being the cost estimation difficult and uncertain (Tsagkari et al., 2016). Almost all literature uses commercial process simulators (e.g. ASPEN Plus®) and their economic simulator software (i.e. ASPEN economic analyzer®) for performing the economic assessment of individual biorefineries. As an example, Attard et al., (2015) studied the economic assessment of waxes extraction as part of a maize stover biorefinery.

The use of FW as feedstock for biorefineries is at an early stage of development and essential elements to assess the viability of a FW biorefinery concept include: (1) estimating the available quantity of the FW to be used as feedstock; (2) analysing to which extent the waste-based production process is less resource intensive than the manufacturing of the same products from virgin material; and, (3) comparing alternative valorisation paths considering both the economic and the environmental dimensions. FW biorefineries may play a relevant role in the so-called resource revolution (Heck and Rogers, 2014). However, it has to be verified if the FW biorefinery concept may lead to what the resource revolution entails, e.g. 50-80% productivity improvement relatively to the virgin material process, a payback period of around two years or less, and the possibility of small-scale applications.

In the literature, the most common approach used to assess the viability of a FW biorefinery is to perform an economic assessment integrating fuel/energy production with value added products e.g. from citrus waste (Lohrasbi et al., 2010) or from the spent pulp of berrys (Davila et al., 2017) . Some studies present an economic assessment of specific FW biorefineries focusing exclusively on value-added chemicals such as the production of pectin and other products from citrus wastes (Davila et al., 2015), the antioxidant production from olive wastes (Hernandez et al., 2014) or the production of biopolymers from waste streams of the animal processing industry (Shahzad et al., 2017). Davila et al. (2015) and Hernandez et al. (2014) included in their studies the environmental dimension using the waste reduction algorithm (WAR) developed by the US Environmental Protection Agency.

Knowing the available quantity of FW is crucial to assess the economic viability of FW biorefinery plants. However, as highlighted by Pfaltzgraff et al. (2013), data on the exact amount of FW produced from food processing is very limited. Therefore, there is a strong need to reduce uncertainty about the volume of FW available (Cristóbal et al., 2016; Corrado et al., 2017) and include this information in the assessment of the economic viability of the biorefinery plants (Imbert, 2017). Up to now, and up to the knowledge of the authors, there is no literature that has performed a general techno-economic analysis of FW biorefineries at the European level taking into account the available quantity of FW streams. Therefore, the aim of this work is to present a techno-economic and profitability analysis of the biorefinery concept in Europe to produce value-added products from specific FW as feedstock. The study includes the quantification of available FW generated from the food processing stage in Europe. Four FW streams were selected and different number of plants (related to the plant processing capacity) distributed across Europe were considered.

2. Material and methods

This section presents the methodology adopted for the FW quantification (sub-section 2.1), the techno-economic and profitability assessment (section 2.2) and a short description of the case studies and valorisation pathways analysed (section 2.3).

2.1 Quantification of FW

The general framework followed for the quantification of FW along the FSC is presented in Fig. 1. Data from EUROSTAT about agricultural production, manufactured goods production (Prodcom) (EUROSTAT, 2017a) and trade flows (i.e. import and export, both from agricultural production and manufactured goods) were retrieved. From these data, and considering assumptions from literature for food losses and wastes at each stage of the FSC (from now on referred as FW), a mass balance was performed (i.e. Consumed =Produced+Imported-Exported-Wasted). As a result, a Sankey diagram was obtained with the quantities of FW by FSC step (i.e. industrial production, distribution, retail and consumption). Details on calculations are reported in the supplementary material.

[Figure 1]

To produce value-added products in biorefineries using FW as feedstock, high levels of homogeneity are required. Moreover, the FW generation sites should not be very scattered to facilitate collection. Based on this considerations, this work was focused on FW generated in the food processing stage (i.e. process waste in Fig. 1) as this may ensure both higher compositional homogeneity and generation of high quantities in specific locations (i.e. the industrial plants).

Biomass transportation needs limit the optimal size of the plants since large plants demand larger distances to acquire the biomass and long distances are especially harmful for feedstocks with high concentration of water or organic components (de Jong and Jungmeier, 2015). In this study, depending on the FW processing capacity (i.e. size) of a single plant, a variable number of plants (from 7 to 70) installed across Europe was considered.

2.2 Techno-economic and profitability assessment

The techno-economic and profitability assessment is divided in the calculation of costs (total capital investment and costs of manufacturing (see Fig. 2)) and the calculation of revenues and profitability ratios. A description on the methodology used for the calculations is presented in the following sub-sections.

[Figure 2]

2.2.1. Total capital investment

Due to the low TRL and the lack of information for most biorefinery processes, an early capital cost estimate was done, also known as ballpark estimate or guesstimate. This kind of estimation rely on escalation factors based on existing similar plants, equipment lists, or conceptual block diagrams indicating major processes steps to predict capital costs. A review of the three widely used techniques (i.e. exponential estimating, factorial estimating, and significant process step estimating) and the most used methods for capital cost estimation can be found in Tsagkari et al. (2016) . Due to the lack of historical and relevant equipment cost data for biorefineries, the exponential and the factorial estimating techniques could not be used. For this study, a significant process step estimating technique (i.e. a functional unit method) (Tsagkari 2016) which postulate the capital cost as a function of major process steps and parameters (e.g. capacity, temperature, pressure and construction materials) was used.

Many of the existing capital cost estimation methods introduce in their correlations the attribute of capacity (intended as the amount of product that a plant can produce within a given period, usually a year). The main problem of adopting this approach is that, usually in biorefineries that produce value-added products, the conversion reaction is very low, and therefore the capacity value is much lower than the values used for the correlation. For this reason, in this study the linear correlation presented by Bridgewater (Eq. 1) that makes use of the throughput (i.e. the amount of material passing through the process per year) was used.

$$\mathrm{ISBL} = \left[401600 + 1.304\left(\frac{\mathrm{Q}}{\mathrm{s}}\right)\right]\mathrm{N} \qquad (1)$$

where (Q/s) represents the throughput of the plant (calculated as shown in Eq. 2), being Q the plant capacity and s the conversion factor (the efficiency at which the reactor is converting raw materials into a product), and N the number of functional units. The most common definition of "functional unit", used in this study, is the following: "A functional unit is a significant step in a process and includes all equipment and ancillaries necessary for operation of that unit. Thus, the sum of the costs of all functional units in a process gives the total capital cost" (Gerrard, 2000).

$$\left(\frac{\mathrm{Q}}{\mathrm{s}}\right) = \frac{\text{Total residues}}{\text{Number of plants}} \qquad (2)$$

The results given by the Bridgwater's correlation are in pounds sterling in UK 1976. This cost was then actualized to EUR 2016 as shown in Eq. 3 using the CEPCI (Chemical Engineering Plant Cost Index) (Turton et al., 2008) which values for the years 1976 and 2016 are 192.1 and 533.9, respectively. An exchange rate of 1.67 EUR/pounds was used.

$$\mathrm{ISBL}_{2016} = \mathrm{ISBL}_{1976} \frac{\mathrm{CEPCI}_{2016}}{\mathrm{CEPCI}_{1976}} \left(1.67 \ \frac{€}{£}\right) \qquad (3)$$

This correlation allows the calculation of the ISBL (Inside Battery Limits) that represents only a part of the Total Capital Investment (TCI) as shown in Fig. 2. Thus, in order to calculate the Fixed Capital Investment (FCI), the Outside Battery Limits (OSBL) and the Indirect Capital Costs (ICC) were estimated using the factors reported in Perry and Green (1999) (Table 9-51) and added to the ISBL. Note that those factors will vary depending if the process under assessment is solid, solid-fluid or fluid processing. Finally, according to Douglas (1988), the Working Capital (reported as 10-20% of TCI) and the Start-up Expenses (reported as 8-10% of the FCI) were calculated and added to the FCI to obtain the TCI.

2.2.2. Manufacturing costs

The cost of manufacturing (COM) associated with the day-to-day operation of a biorefinery was calculated using the correlation presented by Turton et al. (2008) as shown in Eq. 4.

$$\mathrm{COM} = 0.28\mathrm{FCI} + 2.73\mathrm{C}_{\mathrm{OL}} + 1.23(\mathrm{C}_{\mathrm{UT}} + \mathrm{C}_{\mathrm{WT}} + \mathrm{C}_{\mathrm{RM}}) \qquad (4)$$

The variables in this equation are:

- **FCI - Fixed Capital Investment** which calculation has been detailed in section 2.2.1.
- **C_{OL} - Cost of Labor** was calculated considering the number of operators per shift (N_{OL}) multiplied by the annual salary of operators. The N_{OL} was estimated using the correlation by Alkayat and Gerrard (1984) (Eq. 5)

$$N_{OL} = \left(6.29 + 31.7P^2 + 0.23N_{np}\right)^{0.5} \quad (5)$$

where P is the number of processing steps involving the handling of particulate (at most two) and N_{np} is the number of non-particulate processing steps that, according to Turton et al., (2008), is the sum of the number of machineries in the plant (i.e. compressors, heaters, reactors, exchangers, etc.). In order to estimate the C_{OL}, it was considered that the biorefinery operates 8760 h per year and the average hourly labor cost in EU-28 was considered to be 25 EUR/h (i.e. yearly salary for a 2000 h-year is 50000 EUR/year (EUROSTAT, 2017b). The C_{OL} depends considerably on the location of the plant, and significant variations from the above figure may be expected.

- **C_{WT} - Cost of waste treatment** was considered negligible since the waste of the different processes can be used as fuel in cogeneration systems, utilized further downstream in the biorefinery process or incorporated back into the soil for the uptake of nutrients (Attard et al., 2015). Concerning reactants used in the different processes, it was assumed that little or no waste was generated since they are usually recycled in the process.

- **C_{RM} - Cost of Raw Materials** includes several components: (i) the price of the feedstock (i.e. FW) that was considered zero since it is a waste (maybe in the future those wastes will have certain value in the market and their price should be included); (ii) the cost of all the pre-processing steps before entering the biorefinery (e.g. drying); (iii) the price for all the chemicals and reactants (e.g CO_2, ethanol, etc.) used in the biorefinery (Turton et al., (2008) reported a list of prices of common chemicals by August 2006); and, (iv) the cost of transporting the FW to the biorefinery.

For the calculation of the transport distances and costs, both literature and Prodcom data (that provides the percentage of wastes produced in each country) were used. In line with these data, it was assumed that, when the minimum number of biorefinery plants is modelled (i.e. 7), those plants will be located in the countries where the FW is produced in higher quantities (normally higher than 15%) and the FW produced in the rest of the countries will be transported by road. On the other hand, when the maximum number of plants is modelled (i.e. 70), each waste producing country will have at least one plant (or at least close enough to the border) that will make the transport minimum. International transportation distances between waste-producing countries and biorefineries were determined by using online map kilometres from cities located near the ideal centre of the two counties. Intra-national transportation distances were calculated as the half of the distance from an ideal centre of the country to its border. A transportation cost function was calculated depending on the number of plants. An average cost of 0.14 EUR/tkm was used (Schade et al., 2006), considering freight transport by road using a truck.

- **C_{UT} - Cost of Utilities** is directly influenced by the cost of fuels. It includes the cost of all utility streams required by the processes in the biorefinery being the most relevant (but not limited to): fuel gas, oil, coal, electric power, steam, cooling and process water and refrigeration. When electricity and/or heat (obtained from natural gas) were needed in the process, average European prices from EUROSTAT (EUROSTAT, 2017c; 2017d) were considered (0.125 EUR/kWh and 0.0083 EUR/MJ, respectively).

2.2.3. Revenues and profitability ratios

The last section of the techno-economic and profitability assessment is the calculation of the revenues obtained from selling the final biorefinery products in the market. To calculate the quantity of product exiting the biorefinery at industrial scale, laboratory results were scaled-up under the assumption that the same performance would be obtained, if the same process conditions were used (Allbarelli et al., 2016).

Since the market value for the different value-added products from the biorefineries reported in literature and found in the market (MERCK, 2017) are uncertain and volatile, three different scenarios considering low, medium, and high market prices were tested. These scenarios will serve as an indicator to see the order of magnitude of the price at which the biorefinery would be profitable.

Finally, to evaluate the feasibility of the proposed scenarios, two profitability ratios were calculated: Return on Investment (ROI) and Payback time (Eq. 6 and 7, respectively) (Allbarelli et al., 2016), considering a 15 % per year interest rate, 25 years project lifetime and 30 % tax rate.

$$\mathrm{ROI}\ (\%) = \frac{\text{annual net profit}}{\text{total capital investment}} \tag{6}$$

$$\text{Payback time (years)} = \frac{\text{total capital investment}}{\text{annual net profit}} \tag{7}$$

The ROI is the ratio of gains to cost and it measures (in %), per period, the rate of return on money invested in the biorefinery. A positive ROI means that the investment's gains compare favourably to its cost and the larger the ROI, the better. The Payback time is the length of time that it takes for the gains from the investment to equal the costs, namely it measures the time it takes for an investment to pay for itself. The smaller the Payback time, the better.

2.3 Selection of case studies and valorisation pathway

Four agricultural food products were selected as case studies: the two most important vegetable crops worldwide, i.e. potato and tomato, and two relevant crops for Europe and especially for the Mediterranean region, i.e. orange and olive (Mirabella et al., 2014). The selection of the valorisation pathways was done considering those reported as more promising, with more data available, and as being inspired by green chemistry principles and, hence, supposedly with lower environmental impacts. The selected valorisation pathways were the following:

- Tomatoes - extraction of lycopene and β-carotene from tomato wastes using supercritical fluid extraction with CO_2 as supercritical fluid ($SFECO_2$). The biorefinery proposed by Kehili et al., (2016) was used as a model for scaling the results.
- Potatoes - extraction of three phenolic acids, i.e. neochlorogenic, chlorogenic and caffeic acids and three glycoalkaloids, i.e. alfa-chaconine, alfa-solanine and solanidine with a low pressure solid-liquid extraction (Meireles, 2009) using a mixture of water and ethanol (H_2O+EtOH) with acetic acid. The biorefinery data from Maldonado et al. (2014) were used.
- Oranges - extraction of essential oils (EO), pectin and phenolics using a solvent free extraction process that uses Microwave Hydrodiffusion and Gravity,

Microwave Assisted Extraction, and Ultrasound Assisted Extraction. The biorefinery data from Boukroufa et al., (2015) were used.

- Olives - extraction of phenolic compounds (mainly hydroxytyrosol), fatty acids methyl ester (FAME) and squalene using a $SFECO_2$ with EtOH as cosolvent. The biorefinery data from Schievano et al., (2015) were used.

Detailed information about alternative technologies, the rational for the selection, and the flow diagram of the selected pathways can be found in the supplementary material.

3. Results and discussion

We applied the methodology to the selected products, assessing the quantity of waste potentially available, defining the functional units in the process, and performing the techno-economic and profitability assessment. The reference year was the one for which most recent Eurostat data were available. To illustrate the calculations in detail, the orange case study is presented in section 3.1. Detailed information concerning the FW quantification and the techno-economical and profitability assessment for the tomato, potato, and olive case studies and further information for the orange is provided in the supplementary material. Section 3.2 summarizes the findings for the four products.

3.1 Orange case study

3.1.1 Quantification of FW

In Europe, orange production accounts for around the 60% of the citrus production (Sharma et al., 2016). In 2014, the European orange production was equal to 6.3×10^6

t/year. As reported by Sharma et al., (2016) citrus wastes resulting from the citrus processing account for about 50% of their weight (mainly composed of skins, pulp and seeds). Thus, the industrial FW of oranges was estimated as 3.18×10^6 t/year (Sankey diagram and further details on the quantification are provided in the supplementary material section 4). The major orange products producers, and therefore, of waste from manufacturing, according to Prodcom were Germany, France and Spain with 23%, 20% and 19%, respectively.

3.1.2 Techno-economic and profitability assessment

The ISBL was calculated using the Bridgwater's correlation (Eq. 1 and Eq. 3). The valorisation pathway was characterised by five functional units (N): crashing/sizing, Microwave Hydrodiffusion and Gravity (MHG), Microwave Assisted Extraction (MAE), Ultrasound Assisted Extraction (UAE) and purification. Then, considering that the extraction process is a solid-fluid process, the FCI and the TCI were calculated using the values reported in Perry and Green (1999) and the middle values for working capital and start-up expenses. Results for (Q/s), ISBL, FCI and TCI are shown in Table 1 in function of the number of plants.

[Table 1]

For the calculation of the COM for one biorefinery plant, the five elements present in Eq. 4 were estimated.

1. The FCI was calculated as described above and shown in Table 1.
2. For the $C_{OL,}$ Eq. 5 is based on data from chemical plants with a low number of processing steps involving the handling of particulate (i.e. P). When P is higher

than two it is recommended to ignore the middle term and add one operator per solids step. In the case analysed in this study, P was equal to six (i.e. charge and discharge of the three extraction vessels) and N_{np} (i.e. the number of non-particulate processing steps) equalled six (i.e. crusher, MGH, USE, MWE, filtration and purification unit). Solving the equation gives a value of N_{OL} equal to 8.8 that is the number of operators required to run the process unit per shift. The number of operators required for one operator per shift is 4.5 operators. The needed operating labour, without including any support or supervision staff, is equal to (4.5×8.8=39.5) 40 operators per plant. The C_{OL} for one plant is equal to 2×10^6 EUR/year.

3. The C_{WT} was considered negligible since wastes can be utilized further downstream in the biorefinery process.
4. For the $C_{RM,}$ since the analysed valorisation pathway is solvent-free and there is no need for drying the raw material, only the transport cost is calculated. A linear function (Eq. 8) calculated from the maximum transport scenario (with 7 plants located in France, Spain, Germany and UK) and the minimum transport scenario (with 70 plants) was used for calculating the transport distances (in tkm) depending on the number of plants.

$$\text{Distance (in tkm)} = -1 \times 10^7 * N_{\text{plants}} + 2 \times 10^7 \quad (8)$$

5. For the C_{UT} calculation, the cost of the electricity used in the three main units (i.e. MHG, UAE, MAE) was estimated, being the electricity used in the other two

(crushing and purification) negligible (see supplementary material for further details on the calculation).

Results for C_{RM}, C_{UT} and COM are presented in Table 1.

For the calculation of the revenues obtained with the extraction of the three products from orange peel, the quantity of product extracted was estimated assuming that the extraction efficiency reported in Boukroufa et al., (2015) is maintained: 17.3 g EO/kg peel, 0.59 g TPC/kg peel, and 241.5 g Pectin/kg peel. Therefore, the total production was equal to 5.5×10^{7} kg EO/year, 1.86×10^{6} kg TPC/year and 7.68×10^{8} kg Pectin/year.

Prices found in literature (Davila et al., 2015; Lohrasbi et al., 2010; Ciriminna et al., 2014 and 2015) and in the actual market (MERCK, 2017) range from 1 to 70 EUR/kg for EO, around 360 EUR/kg for TPC and from 10 to 350 EUR/kg for Pectin. Since they are uncertain and volatile, three scenarios (i.e. low, medium and high prices) were tested (Table 2).

[Table 2]

Thus, the total revenues obtained for the Low, Medium and High scenarios were 7.75×10^{9}, 7.75×10^{10} and 7.75×10^{11} EUR/year, respectively. The profitability ratios for the three price scenarios are presented in Table 3.

[Table 3]

3.2 Profitability results discussion

In this section the results obtained for the four products are discussed. For a better understanding of the profitability analysis performed, Table 4 shows an overview of the main data used. Further details of all calculations are presented in the supplementary material.

[Table 4]

The results obtained in the four case studies allow to analyse when a biorefinery concept would be profitable (i.e. ROI positive) at the European level considering a certain number of plants (i.e. from 7 to 70) and a certain market price of the produced high-value compounds (High, Medium and Low prices scenarios as shown in Table 4).

First of all, from the results, it can be estimated the order of magnitude that these products' prices have to reach in the market to make the biorefinery process profitable. For all products except for the oranges, the scenario "High" is always profitable and the scenario "Low" is always non-profitable. It is in the "Medium" scenario that profitability depends on the number of plants installed across EU.

Fig. 3 shows the ROI (i.e. dashed line with markers on the left vertical axis) and Payback time (i.e. markers on the right vertical axis) for the four products analysed in the "Medium" scenario.

[Figure 3]

As shown in Fig. 3, for the "Medium" price scenario, the orange case study is profitable (i.e. ROI positive) for all the number of plants with a ROI ranging from 2% to 10% and a Payback time lower than 0.5 years. Conversely, when looking at the tomato, for prices of lycopene and β-carotene of 40000 and 4000 EUR/kg, respectively, the biorefinery concept would be profitable when up to 63 plants were installed in Europe. However, one should also consider the payback time period in this assessment. The payback period for other biorefinery concepts in real world implementation ranged between 3 and 15 years (Balaman and Selim., 2014), so we could consider that above 15 years the investment would be no attractive. Although 63 plants for the tomato biorefinery would be profitable, the payback time would be almost sixty years and so it would be not attractive for investment.

For the potato biorefinery, for a price of the obtained bioactive compounds of 300 EUR/kg, up to 28 plants would be profitable, being 28 plants in the limit of the reasonable payback period (i.e. almost sixteen years). In the case of the olive biorefinery, for a price of TPC, FAME and Squalene corresponding to 200, 10 and 10 EUR/kg, respectively, up to 42 plants would be profitable but only up to 35 plants would be attractive for investment since the payback time for 42 plants would be around 70 years. As mentioned previously, the market prices for these products are very uncertain and therefore one should have in mind that the analysis herein presented was done so we could have indicative market values for which the biorefinery would be profitable and attractive for investment (payback time lower than 15 years). However, for products with such uncertain market price, the preferable situation for investors would be to have a reasonable ROIs and very low payback time (2 to 3 years) to minimize investment risk. Considering this, the use of FW from oranges would be the most attractive for investment among the case studies analysed since even in the Low market price scenario it presents a ROI ranging from 2% to 10%, with respective payback time of 0.57 to 0.11 years. Nevertheless, a robust market price analysis would be necessary to confirm these values.

3.2.1 Influence of the number of plants in the cost of manufacturing

To highlight possible areas for cost reduction, the contribution of the different costs to the COM depending on the number of plants was calculated and is reported in Fig. 4.

C_{UT} is the cost contributing the most to the COM in the olive and the orange biorefineries independently of the size of the plants. In the tomato biorefinery, the C_{UT} accounts for almost 60% of the COM for big plants but the contribution of this cost is reduced to 24% in smaller plants in which the FCI and C_{OL} account for 33 % each.

[Figure 4]

In the potato biorefinery, due to the high quantity of solvent used in the process, the C_{RM} for big plants is the major contributor with 52%. In this case, C_{UT} represent 20% of COM. On the other hand, for smaller potato biorefineries the FCI and C_{OL} are the highest contributors with almost 40% each.

3.2.2 Sources of uncertainty

The previous analysis and results must be evaluated taking into account the high uncertainty that this kind of study entails. The main sources of uncertainty in this study were:

<u>The cost estimation method.</u> According to Tsagarski et al., (2014) the cost estimation method for low TRL technologies presents a wide accuracy that falls within a range of -30/+30% as a result of failures in inflation projection and cost growth due to unpredictable events related to the high complex process and unproven technology. A sensitivity analysis performed for the tomato case show that the increase of 30% in the ISBL reduce the number of plants that makes the biorefinery concept attractive for investment (i.e. positive ROI and payback time lower than 15 years), being in the base

case around 56 and in the increase 30% scenario around 42. On the other hand, the reduction of 30% in the ISBL increase the number of plants (around 63) that would be attractive for investment.

Revenues. Depending on the composition and purity of the product and the format and quantity in which the product is sold, its price can range around six orders of magnitude. Within the three price scenarios studied, it was concluded that the "Medium" price scenario points out the order of magnitude of the products at which the profitability of the biorefinery depends on the number of plants. A sensitivity analysis showed that the profitability of the biorefineries under study is very sensitive to changes in the selling price of the products in the market.

Cost of Utilities. The electricity and natural gas prices for industrial users in the European Union depend on a range of different supply and demand conditions, including the geopolitical situation, import diversification, network costs, environmental protection costs, severe weather conditions, and levels of excise and taxation (EUROSTAT, 2017d). For this study, average European prices for electricity and natural gas was used but depending on the country this value can be more or less accurate.

Process variables. Laboratory results were used to scale-up the industrial process considering that the same performance would be obtained. However, the quantities of product exiting the biorefinery as well as the whole mass balance are uncertain. There is uncertainty in the efficiency of the product extraction and so the quantity of product available to be sold in the market may change, affecting the revenues.

Wastes. In the present study, wastes were considered to be out of the system boundaries since they could be further utilized in the biorefinery. When those wastes are further used or processed, they obtain a certain value in the market increasing the revenues. On the other hand, if no revenue can be obtained from them, they will have to be properly managed and disposed with the subsequent cost.

Feedstock quantity. The estimation of the FW quantity available for the biorefinery process is uncertain. As mentioned before, due to homogeneity and dispersion criteria, certain FW streams were not considered for the biorefinery process. Besides, product efficiency data from literature was used to estimate the FW produced in industrial processes, but they can vary according to specific conditions (e.g. the quantity of olive mill waste in the olive oil production process can vary from 10% to 20%).

Transport. The quantification of transported quantities and travelled distances are uncertain. Most likely, the total transport cost depending on the number of plants will not be linear as assumed in this study. To present a reliable equation this exercise would benefit from an optimization model to provide a more accurate value.

Further research is needed to quantify the biorefinery profitability in a robust way, considering the uncertainty associated to the market prices along with the rest of the above mentioned uncertainty sources. Other aspects for further research are to: (i) include the cascade use of wastes, integrating other downstream processing steps such as the final biofuel and energy production aiming at "zero wastes"; (ii) capture spatial and temporal dimensions of FW generation; (iii) assess alternative valorisation pathways including the environmental dimension; and, (iv) investigate the integration of valorisation pathways in existing production plants towards a multi FW feedstock biorefinery concept.

4. Conclusions

This study presents the estimations of FW generation at manufacturing stage for four different products at European scale and a techno-economic and profitability analysis of potential routes for their valorisation in biorefineries. The value-added product market price was identified as key element to determine the profitability of the biorefinery highlighting the need of performing a market analysis prior to the biorefinery implementation. It is also important to consider the economies of scale and their effect in profitability as shown in the paper. The screening analysis performed at European level unveiled that not all the waste feedstock have the same potential and that the most profitable options are those related to implementing fewer plants, namely concentrating the production and capitalising on economies of scale. However, the optimization of feedstock availability and transport should be systematically implemented to ensure that the profitability of biorefineries is not leading to trade-offs, such as increasing environmental impacts and externalities.

E-supplementary data of this work can be found in the online version of the paper.

References

Alkayat, W.A., Gerrard, A.M., 1984. Estimating manning levels for process plants. AACE Transactions. 1: 2.1-2.4.

Allbarelli, J.Q., Santos, D.T., Cocero, M.J., Meireles, M.A.A., 2016. Economic analysis of an integrated annatto seeds-sugarcane biorefinery using supercritical CO2 extraction as a first step. Materials. 9: 494 – 513.

Attard, T.M., McElroy, C.R., Hunt, A.J., 2015. Economic assessment of supercritical CO2 extraction of waxes as part of a maize stove biorefinery. Int J Mol Sci. 16: 17546 - 17564.

Balaman, S.Y., Selim, H., 2014. Multiobjective optimization of biomass to energy supply chains in an uncertain environment. Proceedings of the 24th European Symposium on Computer Aided Process Engieneering – ESCAPE24, pp. 1267 – 1272. Editors: Klemens, J.J., Varbanov, P.S., Liew, P.Y. Publisher: Elsevier.

Boukroufa, M., Boutekedjiret, C., Petigny, L., Rakotomanomana, N., Chemat, F., 2015. Bio-refinery of orange peels waste: a new concept based on integrated green and solvent free extraction processes using ultrasound and microwave techniques to obtain essential oil, polyphenols and pectin. Ultrasonics sonochemistry, 24: 72 – 79.

Cherubini, F., 2010. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. Energy conversion and management, 51: 1412 – 1421.

Ciriminna, R., Lomeli-Rodriguez, M., Cara, P.D., Lopez-Sanchez, J.A., Pagliaro, M., 2014. Limonene: a versatile chemical of the bioeconomy. ChemComm., 50: 15288 – 15296.

Ciriminna, R., Chavarria-Hernandez, N., Rodriguez-Hernandez, A.I., Pagliaro, M., 2015. Pectin: a new perspective from the biorefinery standpoint. Biofuels, Bioprod. Bioref., 9: 368 – 377.

Cristobal, J., Vila, M., Giavini, M., Torres De Matos, C., Manfredi, S., 2016. Prevention of Waste in the Circular Economy: Analysis of Strategies and Identification of Sustainable Targets - The food waste example. EUR 28422; Luxembourg (Luxembourg): Publications Office of the European Union; JRC105415; doi:10.2760/256208

Corrado, S., Ardente, F., Sala, S., Saouter, E., 2017. Modelling of food loss within life cycle assessment: From current practice towards a systematization. Journal of Cleaner Production, 140 (2): 847 – 859.

Dahiya, S., Kumar, A.N., Shanthi Sravan, J., Chatterjee, S., Sarkar, O., Mohan, S.V., 2018. Food waste biorefinery: Sustainable strategy for circular bioeconomy. Bioresour. Technol. 248, 2–12.

Davila, J.A., Rosenber, M., Cardona, C.A., 2015. Techno-economic and environmental assessment of p-cymene and pectin production from orange peel. Waste and biomass valorization, 6: 253 – 261.

Davila, J.A., Rosenber, M., Cardona, C.A., 2017. A biorefinery for efficient processing and utilization of spent pulp of Colombian Andes Berry (Rubus glaucus Benth.):

Experimental, techno-economic and environmental assessment. Bioresour. Technol., 223: 227 – 236.

de Jong. E., Jungmeier. G., 2015. Industrial Biorefineries and White Biotechnology. Chapter: Biorfinery Concepts in Comparison to Petrochemical Refineries. Publisher: Elsevier. pp.3-33.

Douglas, J.M., 1988. Conceptual design of chemical processes. Publisher: McGrawHill.

EC – European Commission, 2015. Communication COM(2015) 614/2: Closing the loop – An EU action plan for the Circular Economy. Available online at http://ec.europa.eu/priorities/jobs-growth-investment/circular-economy/docs/communication-action-plan-for-circular-economy_en.pdf

EUROSTAT, 2017a. Manufactured goods (Prodcom). Available online: http://ec.europa.eu/eurostat/web/prodcom

EUROSTAT, 2017b. Wages and labour costs. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Wages_and_labour_costs#Labour_costs

EUROSTAT, 2017c. Electricity price statistics. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

EUROSTAT, 2017d. Natural gas price statistics. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics

Gerrard. A.M., 2000. Guide to Capital cost estimating. Publisher: IChemE.

Heck, S., Rogers, M., 2014. Resource revolution: How to capture the biggest business opportunity in a century. Publisher: McKinsey&Company.

Hernandez, V., Romero-Garcia, J.M., Davila, J.A., Castro, E., Cardona, C.A., 2014. Techno-economic and environmental assessment of an olive Stone based biorefinery. Resources, conservation and recycling, 92: 145 – 150.

Imbert, E., 2017. Food waste valorization options: opportunities from the bioeconomy. Open Agriculture, 2: 195 – 204.

Kehili, M., Schmidt, L.M., Reynolds, W., Zammel, A., Zetzl, C., Smirnova, I., Allouche, N., Sayadi, S., 2016. Biorefinery cascade processing for creating added value on tomato industrial by-products from Tunisia. Biothechnol Biofuels. 9: 261

Lohrasbi, M., Pourbafrani, M., Niklasson, C., Taherzadeh, M.J., 2010. Process design and economic analysis of a citrus waste biorefinery with biofuel and limonene as products. Bioresource technology, 101: 7382 – 7388.

Matharu, A.S., de Melo, E.M., Houghton, J.A., 2016. Opportunity for high value-added chemical from food suppy chain wastes. Bioresource technology, 215: 123 – 130.

Maldonado, A.F.S., Mudge, E., Gänzle, M.G., Schieber, A., 2014. Extraction and fractionation of phenolic acids and glycoalkaloids from potato peels using acidified water/ethanol-based solvents. Food research international, 65: 27 – 34.

Meireles, M.A.A., 2009. Extracting bioactive compounds for food products – Theory and applications. Publisher: CRC Press – Taylor & Francis Group.

MERCK, 2017 - http://www.sigmaaldrich.com/germany.html

Mirabella, N., Castellani, V., Sala, S., 2014. Current options for the valorization of food manufacturing waste: a review. Journal of cleaner production. 65: 28 – 41.

Mohan, S.V., Nikhil, G.N., Chiranjeevi, P., Reddy, C.N., Rohit, M.V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. Bioresource technology, 215: 2 – 12.

Monier, V., Mudgal, S., Escalon, V., O'Connor, C., Gibon, T., Anderson, G., Morton, G., 2010. Preparatory study on food waste across EU 27. Report for the European Commission [DG ENV—Directorate C].

Nizami, A.S., Rehan, M., Waqas, M., Naqvi, M., Ouda, O.K.M., Shahzad, K., Miandad, R., Khan, M.Z., Syamsiro, M., Ismail, I.M.I., Pant, D., 2017. Waste biorefineries: Enabling circular economies in developing countries. Bioresource technology, 241: 1101 – 1117.

Ong, K.L., Kaur, G., Pensupa, N., Uisan, K., Lin, C.S.K., 2017. Trends in food waste valorization for the production of chemicals, materials and fuels: Case study South and Southeast Asia. Bioresour. Technol. 248, 100–112.

Perry, R.H., Green, D.W., 1999. Perry´s Chemical Engineers´ Handbook. Publisher: The McGraw-Hill.

Pfaltzgraff, L.A., De bruyn, M., Cooper, E.C., Budarin, V., Clark, J.H., 2013. Food waste biomass: a resource for high-value chemicals. Green chemistry, 15: 307 – 314.

Pommeret, A., Yang, X., Kwan, T.H., Christoforou, E.A., Fokaides, P.A., Lin, C.S.K., 2017. Food Waste reduction and valorization. Chapter 7: Techno-economic study and environmental assessment of food waste based biorefinery. Editors: Morone, P., Papendiek, F., Tartiu, V.E. Publisher: Springer.

Ren, Y., Yu, M., Wu, C., Wang, Q., Gao, M., Huang, Q., Liu, Y., 2018. A comprehensive review on food waste anaerobic digestion: Research updates and tendencies. Bioresource Technology, 247: 1069 – 1076.

Schade. W., Doll. C., Maibach. M., Peter. M., Crespo. F., Carvalho. D., Caiado. G., Conti. M., Lilico. A., Afraz. N., 2006. COMPETE Final Report: Analysis of the contribution of transport policies to the competitiveness of the EU economy and comparison with the United States. Funded by European Commission – DG TREN. Karlsruhe. Germany.

Schievano, A., Adani, F., Buessing, L., Botto, A., Casoliba, E.N., Rossoni, M., Goldfarb, J.L., 2015. An integrated biorefinery concept for olive mill waste management: supercritical CO2 extraction and energy recovery. Green Chemistry, 17: 2874 – 2887.

Shahzad, K., Narodoslawsky, M., Sagir, M., Ali, N., Ali, S., Rashid, M.I., Ismail, I.M.I., Koller, M., 2017. Techno-economic feasibility of waste biorefinery: Using slaughtering waste streams as starting material for biopolyester production. Waste Manag. 67, 73–85.

Sharma, K., Mahato, N., Cho, M.H., Lee, Y.R., 2016. Converting citrus wastes into value added products: Economical and environment-friendly approaches. Nutrition, doi: 10.1016/j.nut.2016.09.006.

Tsagkari, M., Couturier, J.L., Kokossis, A., Dubois, J.L., 2016. Early-stage capital cost estimation of biorefinery processes- a comparative study of heuristic techniques. Chemsuschem. 9: 2284 – 2297

Turton, R., Bailie, R.C., Whiting, W.B., Shaeiwitz, J.A., 2008. Analysis, Synthesis and Design of Chemical Processes. Third Edition. Publisher: Prentice Hall.

UN – United Nations, 2015. Available at: http://www.un.org/sustainabledevelopment/sustainable-development-goals/

Yang, X., Lee, S.J., Yoo, H.Y., Choi, H.S., Park, C., Kim, S.W., 2014. Biorefinery of instant noodle waste to biofuels. Bioresource technology, 159: 17 – 23.

Figure Captions

Fig. 1. Food waste estimation framework.

Fig. 2. Total capital investment and cost of manufacturing calculation framework

Fig. 3. Results for the "Medium" price scenario for the four waste biorefineries

Fig. 4. Contribution analysis of the Cost of Manufacturing (COM) in the different biorefineries

Tables

Table 1. Costs calculation for the orange waste biorefinery as a function of the number of plants

Number of plants	(Q/s) [×1000 t/year]	ISBL [×10^7EUR]	FCI [×10^7EUR]	TCI [×10^7EUR]	C_{RM} [×10^6 EUR/year]	C_{UT} [×10^7 EUR/year]	COM [×10^7 EUR/year]
7	454.29	2.30	5.29	6.64	38.6	14.5	24.6
14	227.14	1.62	3.72	4.66	18.6	7.23	12.8
21	151.43	1.39	3.19	4.00	11.9	4.82	8.84
28	113.57	1.27	2.93	3.67	8.60	3.62	6.87
35	90.86	1.20	2.77	3.47	6.60	2.89	5.69
42	75.71	1.16	2.67	3.34	5.27	2.41	4.90
49	64.90	1.13	2.59	3.25	4.31	2.07	4.34
56	56.79	1.10	2.53	3.18	3.60	1.81	3.92
63	50.48	1.08	2.49	3.12	3.04	1.61	3.59
70	45.43	1.07	2.45	3.08	2.60	1.45	3.33

Table 2. Price (EUR/kg) scenarios for the orange waste biorefinery products

Product	Low	Medium	High
EO	1	10	100
TPC	10	100	1000
Pectin	10	100	1000

Table 3. Return on Investment (ROI) and Payback time for the orange waste biorefinery considering three price scenarios (Low, Medium and High)

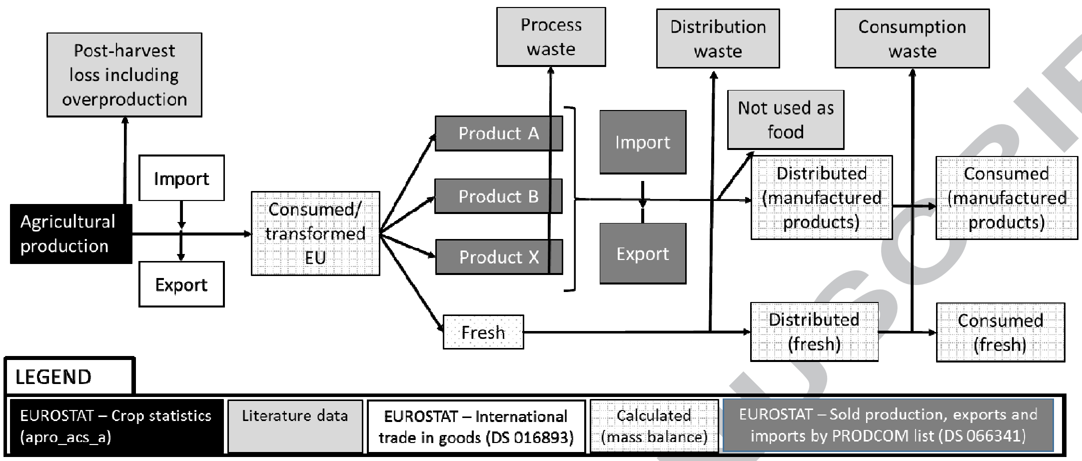
Number of plants	ROI (%)			Payback time (years)		
	Low	Medium	High	Low	Medium	High
7	9.09	114.23	1165.57	0.11	0.01	0.00
14	6.40	81.28	830.09	0.16	0.01	0.00
21	4.91	63.06	644.54	0.20	0.02	0.00
28	3.97	51.50	526.77	0.25	0.02	0.00
35	3.32	43.51	445.38	0.30	0.02	0.00
42	2.84	37.65	385.76	0.35	0.03	0.00
49	2.48	33.18	340.22	0.40	0.03	0.00
56	2.19	29.65	304.28	0.46	0.03	0.00
63	1.95	26.80	275.21	0.51	0.04	0.00
70	1.76	24.44	251.20	0.57	0.04	0.00

Table 4. Overview of data used in the profitability analysis

Input product	Waste amount (t/year)	Valorisation pathway	Output product	Outputs quantity (kg/year)	Price (EUR/kg)		
					Low	Medium	High
Tomato peels	1.48×10^6	$SFECO_2$	Lycopene	3.6×10^4	4000	4×10^4	4×10^5
			β-carotene	2927.2	400	4000	4×10^4
Potato peels	2.34×10^6	Solvent extraction H_2O+EtOH	Neochlorogenic acid	3.1×10^5	30	300	3000
			Chlorogenic acid	1.8×10^6			
			Caffeic acid	1.1×10^5			
			Alfa-chaconine	4×10^5			
			Alfa-solanine	1.66×10^5			
			Solanidine	2341			
Orange peels	3.18×10^6	MHG+MAE +UAE	EO	5.5×10^7	1	10	100
			TPC	1.86×10^6	10	100	1000
			Pectin	7.68×10^8	10	100	1000
Olive mill wastes	4.1×10^6	$SFECO_2$ +EtOH	TPC	4.68×10^6	200	2000	2×10^4
			FAME	3.99×10^6	10	100	1000
			squalene	4.31×10^6	10	100	1000

Highlights

- A techno-economic and profitability analysis of a food waste biorefinery is presented
- Four relevant products were analysed: potato, tomato, citrus fruits and olives
- Food waste from the products processing was quantified at the European level
- The value-added product market price was identified as key element for profitability
- A market analysis is necessary prior the biorefinery implementation



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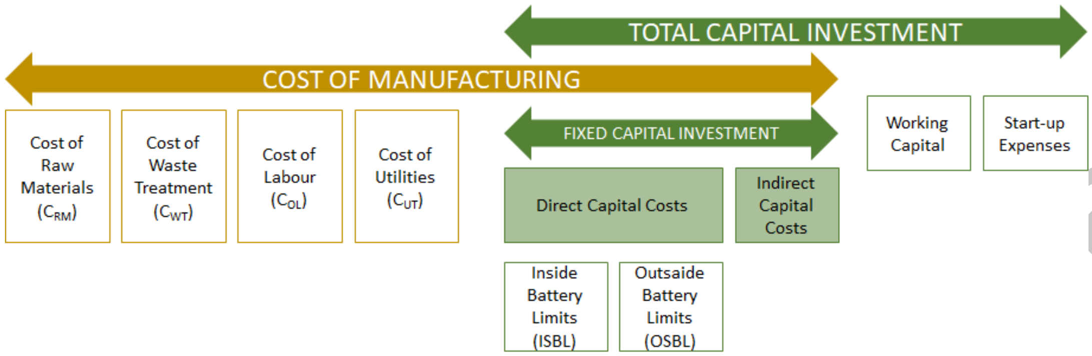

Fig. 2. Total capital investment and cost of manufacturing calculation framework

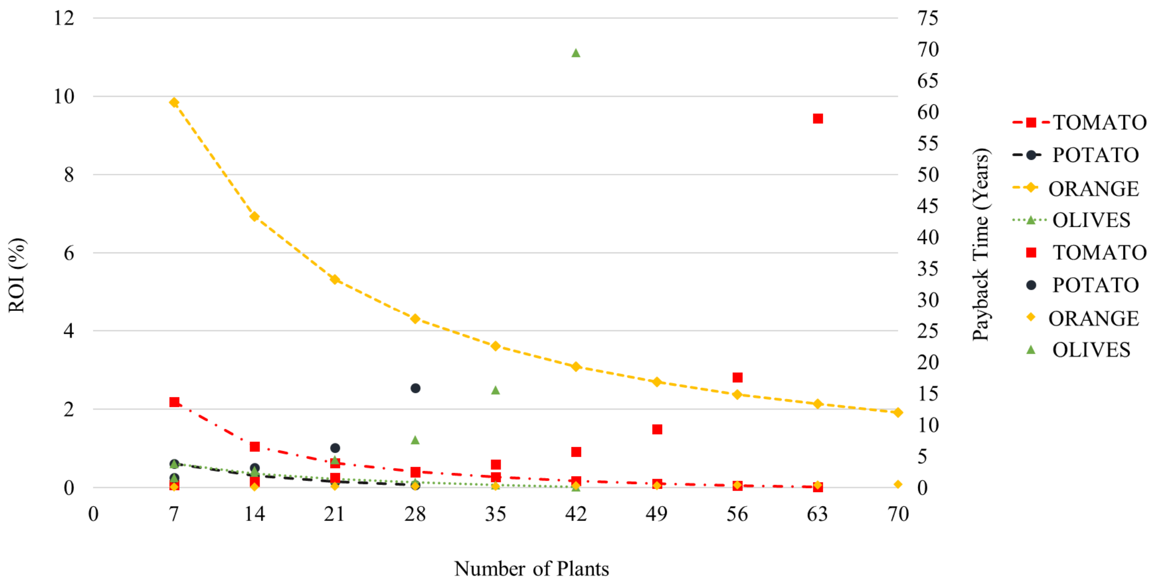

Fig. 3. Results for the “Medium” price scenario for the four waste biorefineries

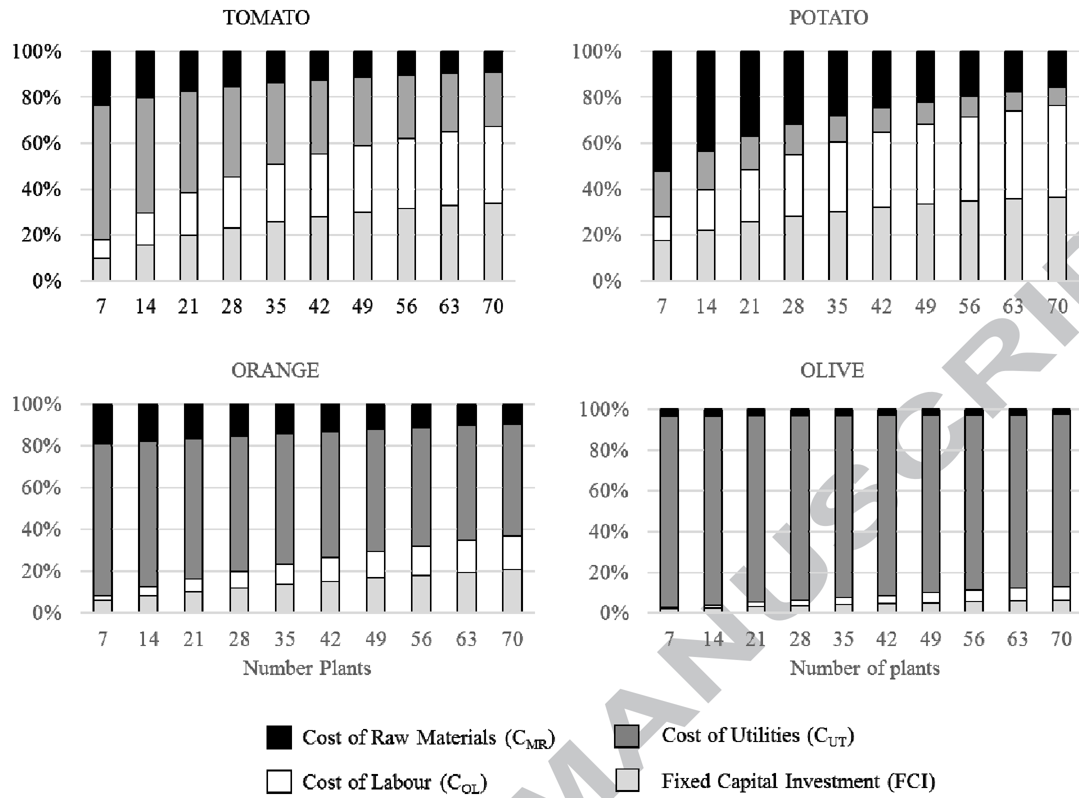

Fig. 4. Contribution analysis of the COM in the different biorefineries