

Sustainable production of bio-based chemicals and polymers via integrated biomass refining and bioprocessing in a circular bioeconomy context

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Abstract

The sustainable production of bio-based chemicals and polymers is highly dependent on the development of viable biorefinery concepts using crude renewable resources for the production of diversified products. Within this concept, this critical review presents the availability of fractionated co-products and fermentable sugars that could be derived from major industrial and food supply chain side streams in EU countries. Fermentable sugars could be used for the production of bio-based chemicals and polymers. The implementation of biorefinery concepts in industry should depend on the evaluation of process efficiency and sustainability including techno-economic, environmental and social impact assessment following circular bioeconomy principles. Relevant sustainability indicators and End-of-Life scenarios have been presented. A case study on the techno-economic evaluation of bio-based succinic acid production from the organic fraction of

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municipal solid waste has been presented focusing on the evaluation of process profitability and feedstock requirement.

Keywords: circular bioeconomy, sustainability assessment, End-of-Life scenarios, bio-based chemicals and polymers, succinic acid, biorefinery

1. Introduction

The production of bio-based chemicals and polymers depends on the utilisation of renewable resources, such as agricultural crops and associated residues, forestry residues, marine biomass resources, industrial side streams and food supply chain side streams. According to Pleissner et al. (2016), around 3.7×10^9 t of agricultural residues and 1.3×10^9 t of food residues occur annually worldwide. Mohammed et al. (2018) mentioned that the USA agriculture can probably support up to 155 million t of residues for producing bioenergy in 2030, without the need for additional land requirement since these residues are derived from major crops. Forestry residues are mainly used for heat and electricity production (Gonçalves et al., 2018) as well as for the production of bio-based products (Frankó et al., 2016). This critical review focusses on the evaluation of industrial and food supply chain side streams (IFSS) as feedstocks for biorefinery development integrated with the production of bio-based chemicals and polymers via bioprocessing.

According to the Food and Agriculture Organisation (FAO) food losses refers to "*the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption*" (Gustavsson et al., 2013). Global estimates of waste production at different stages of the food supply chain, including (i) production, (ii) postharvest, (iii) handling and storage, (iv) processing and packaging, (v) distribution and retail, (vi) consumer losses, are provided in the 2011 FAO report. Approximately 1.3 billion t per year of food losses, corresponding to the one third of global food production (Gustavsson et al., 2013), is lost or wasted. This corresponds to 614 kcal/cap/day, which is ¼ of an average nutrition uptake (Kummu et al., 2012). The carbon footprint of these specific losses is estimated at 3.3 billion t of CO_2 equivalent of greenhouses gasses (GHG) released into the atmosphere and a direct economic loss (excluding fish and seafood) of $750 billion annually (FAO, 2013). The FAO report published in 2019 estimates the Food Loss Percentage and the Food Loss Index at all stages of the food supply chain, excluding retail. The Food Loss Index (composite of commodities in agricultural and food systems: crops, livestock and fisheries) shows the positive and negative trends towards reduction of losses in a base of 100. The previous study overestimated food waste, as all non-food applications for feed, seed or industrial uses, were considered as waste. The 2019 FAO report takes into consideration such non-food uses. Current Sustainable Development Goals aim for the reduction of global quantities of food waste per capita, in half at the retail and consumer levels and for the reduction of food supply chain waste (including post-harvest losses) by 2030 (UNFAO, 2019). According to the estimations of the 2019 FAO report, 14 % of food losses occur at the post-harvest stage up to the retail stage (UNFAO, 2019).

Koutinas et al. (2014) presented potential bio-based chemicals and polymers that could be produced via bioprocessing as well as various IFSS that could be used as feedstock for biorefinery development. However, it is critical to quantify feedstock availability and also the geographic distribution of relevant IFSS feedstocks in order to assess the fermentative production of bio-based chemicals and polymers within a biorefinery concept. It is nowadays common knowledge that conventional fermentation processes are less cost-competitive than petrochemical processes. For this reason, biomass refining should be optimized taking also into consideration the assessment of techno-economic, environmental and social impacts in comparison to relevant benchmarks (e.g. relevant petrochemical products). Biorefinery development should also include circular bioeconomy principles involving a suitable combination of End-of-Life (EoL) scenarios (e.g. mechanical, chemical, energy, nutrient recycling) in order to enhance process sustainability.

This critical review presents the geographic distribution and availability of representative IFSS in EU countries. The potential separation of specific fractions (e.g. protein, lipids, pectin) that could be used for the production of value-added co-products has been also illustrated. Sustainability indicators and EoL scenarios that could be used for sustainability assessment and the development of circular biorefinery concepts have been presented. Finally, a case study on techno-economic evaluation of succinic acid production from the organic fraction of municipal solid waste has been presented in order to illustrate process profitability assessment and resource requirements.

2. Resource efficiency and biorefinery development using industrial and food supply chain side streams

Biorefinery development should be employed for the production of value-added bio-based products from different renewable resources (Moncada et al., 2016), such as agricultural residues, forestry residues, algal biomass and IFSS. The first two residues are characterized as lignocellulosic biomass. According to Rodias et al. (2019), one of the energy crops that are mainly cultivated for biomass, biogas or other biofuels production is yellow biomass which is referred to residues derived from any crop cultivation (e.g. corn stover, wheat straw). The construction of industrial plants in the optimal location is directly associated with crop residue-related parameters (e.g. quantity, accessibility, weather conditions, etc.). Monforti et al. (2013) estimated the potential for bioenergy production from agricultural residues by evaluating the geographic distribution of eight agricultural crops and the possible optimal location of the power plants. The estimated crop residues in EU could support around 850 plants, which are expected to produce annually about 150×10^{10} MJ of bioenergy. According to Thorenz et al. (2018), Scandinavian and Central European countries show the most stable supplies of coniferous bark, a very common forestry residue. In the case of algal biomass, Bhowmick et al. (2019) describes the “zero waste discharge” concept in which strategies for the production of biofuel, biochar and bio-based products utilizing wastewater in a biorefinery model are adopted. More specifically, microalgae is cultivated for the production of bioenergy and biofuels with simultaneous use of the microalgal remaining fractions for biochar production as a co-product. Laurens et al. (2017) and Rashid et al. (2013) mention that the remaining microalgal biomass, has a wider variety of uses, such as water purification and soil amendment properties.

Previous studies have focused on the evaluation of agricultural and forestry residues and algal biomass for the production of biofuels, energy, food, feed and bio-based chemicals and polymers. This study presents the biorefinery development potential of IFSS in EU-28. The Eurostat has been used in order to estimate the production capacities of representative side streams in EU-28 in 2016 derived from different industrial sectors (e.g. juice processing, breweries, wineries, sugar production from sugar beet, pulp and paper industry) and municipal solid waste. The side streams derived from the industrial processes were estimated from relevant process flow sheets. Representative literature-cited compositions of all IFSS were used in order to calculate the protein, lipids, pectin and carbohydrates that could be separated from these side streams (Table 1). The geographic distribution was based on the fermentable sugar content of IFSS considering as the limiting factor the fermentative production capacity of around 50,000 t of a platform chemical where it is expected that economies of scale have been reached. Considering an overall sugar to fermentation product conversion yield of around 0.5 g/g, then a carbohydrate availability of around 100,000 t will be required to enable the development of such a biorefinery. In the following sections, the geographic distribution and availability of fermentable sugars of representative IFSS in EU countries has been presented.

2.1. Fruit and vegetable processing

Around 132.96 million t of fruit and vegetables were produced in EU in 2016 according to FAOSTAT. In 2016, juice production in EU was 11.38 million t according to Eurostat data. Based on the AWARENET report (2004), the solid side streams produced from the juice production process of fruit and vegetables represents 30-50 % of the initial raw material. Considering an average percentage of 40 % and juice production data from Eurostat (11.38 million t), approximately 7.58 million t of solid side streams were produced in 2016 in EU-28 from the juice production industries.

The composition of solid side streams varies depending on the fruit used as raw material. Assuming that 60 % of the produced juice comes from oranges (35 %) and apples (25 %), the potential fermentable sugar availability has been estimated considering their content in soluble sugars (22.9% and 10.8-15.0%), cellulose (22% and 7.2-43.6%) and hemicellulose (11.2% and 4.3-24.4%) as presented in Table 1. Fermentable sugars from orange peels and apple pomace at quantities higher than 100,000 t will be available in 2 countries, in particular Germany (ca. 150×10^3 t/year) and Spain (ca. 105×10^3 t/year). Hydrolysates from fruit and vegetables processing have been used for the production of D-lactic acid (de la Torre et al., 2019).

Figure 1 presents the potential fermentable sugars and value-added fractions (e.g. D-limonene, pectins) that can be extracted from orange peels within a biorefinery concept. For instance, the fungal strain *Trichoderma reesei* QM6a Δgar1 udh has been used for the production of galactaric (mucic) acid from D-galacturonic acid derived via pectin hydrolysis (Paasikallio et al., 2017).

Similar to juice production, more than 27 million t of processed and preservation products from fruit and vegetables were produced in EU-28 in 2016. According to the AWARENET report (2004), the percentage of the solid side streams produced from preservation processes ranges from 5 % to 30 % depending on the fruit or vegetable that is used as raw material. Thus, around 5.73 million t of solid side streams were produced in 2016 in EU-28 from fruit & vegetables preservation processes.

2.2. Breweries

Around 39.9 million t of beer were produced in EU-28 in 2016 with Germany (8.68 million t) and UK (5.15 million t) being the main producers (Eurostat, 2016). Brewer's spent grain (BSG) and spent yeast are the main by-products derived from breweries. BSG corresponds to around 30 % (w/w) of the starting material and accounts to 85 % of the total by-product generation in breweries

(Tang et al., 2009). Approximately, 270 kg of solid wastes are produced from the production of 1 cubic meter of beer. The overall BSG generated by breweries in EU-28 in 2016 was around 10.8 million t. BSG has a high polysaccharide content (cellulose and hemicellulose content 36.0-67.9 %, db, Table 1) and a significant protein content (15.3-24.7 %, db, Table 1). BSG is currently mainly used as animal feed (Lynch et al., 2016). Mussatto et al. (2013) has developed a biorefinery concept using BSG for the production of xylitol, lactic acid, activated carbon and phenolic acids. Initially, the hemicellulose fraction is hydrolyzed, while the cellulose and lignin fractions are treated via soda pulping. The black liquor derived from lignin processing is processed in a phenolic acid and activated carbon plant. Chemical pre-treatment and enzymatic hydrolysis of BSG has been employed for the production of a hydrolysate that was subsequently used in fermentations carried out by *Lactobacillus delbrueckii* for the production of 35.5 g/L lactic acid with a productivity of 0.59 g/L/h (Mussato et al., 2008).

Figure 2 presents the potential fermentable sugars and other value-added fractions (e.g. lipids, phenolics, protein isolate) that could be derived from BSG in EU-28 countries. The geographic distribution of BSG could be regarded as poor, considering platform chemical production via fermentation, because BSG is only available in four EU-28 countries at quantities higher than 100,000 t per annum, including Germany (ca. 327×10^3 t/year) and UK (ca. 194×10^3 t/year) as the predominant ones.

2.3. Wineries

Wine production in EU was estimated at more than 16.16 million t of red and white wine in 2016. The main producers are Spain (4.22 million t), Italy (3.78 million t) and France (3.47 million t) producing more than 75 % of the wine in EU-28 (Eurostat, 2016). The main side streams from wine making processes are wine lees, grape pomace, grape seeds and stalks. According to the AWARENET report (2004), the total solid side streams of wine production processes (red or white) are 20-30 % of incoming grapes. Based on the data for wine production and by taking into consideration the average side stream generation (25 %), 5.4 million t of side streams were produced in 2016 in EU-28 from both red wine and white wine making processes. More than 4 million t of side streams are available in Spain, Italy and France.

Winery side streams may provide around 659×10^3 t of fermentable sugars per year, based on the average content of the composition range presented in Table 1 (Figure 3). Winery waste refining may also lead to the production of various value-added fractions (Figure 3). Grape pomace contains residual sugars that can be extracted and used as carbon source for fermentative production of bio-based chemicals and polymers. Furthermore, grape seed oil could be also extracted as a value-added co-product. The remaining solids from grape pomace and grape stalks could be thermochemically and enzymatically treated to produce a hydrolysate rich in fermentable sugars. Wine lees represent 2-6% of wine production and they are rich in phenolic compounds, residual ethanol and tartrate salts that could be extracted as co-products (Dimou et al., 2016). The remaining fraction of wine lees is rich in yeast biomass and could be converted into a nutrient-rich hydrolysate. The sugar-rich and the nutrient-rich hydrolysates constitute a fermentation feedstock for the production of various bio-based chemicals and polymers.

The geographic distribution of winery waste could be regarded as poor, considering platform chemical production via fermentation, because winery waste is only available in three EU-28 countries at quantities higher than 100,000 t per annum, including Spain (ca. 184×10^3 t/year), Italy (ca. 164×10^3 t/year) and France (ca. 151×10^3 t/year).

2.4. Sugar beet processing

Sugar beet pulp (SBP) is the main solid by-product of the European sugar production industry. According to FAOSTAT, the total amount of SBP that was generated in 2016 in EU-28 is ca. 10.35 million t/y. The fermentable sugars that can potentially be produced from this stream in EU-28 is 5.2 million t/y, if we take into consideration the composition of the SBP (7.1 % free sugars, cellulose and hemicellulose 42.5 %, db, Table 1). SBP is mainly used as animal feed. Figure 4 presents the potential fermentable sugars and value-added fractions that could be derived from SBP in EU-28 based on the process developed by Alexandri et al. (2019). The fermentable sugar availability derived from SBP is higher than 100,000 t in seven EU-28 countries, including France (ca. 1,035×10^3 t/year), Germany (ca. 810×10^3 t/year), Poland (ca. 405×10^3 t/year) and UK (ca. 170×10^3 t/year) as the major producing countries. Alexandri et al. (2019) presented a biorefinery concept for the separation of a phenolic rich extract and pectin followed by chemical and enzymatic hydrolysis of the carbohydrates for the production of bio-based chemicals and polymers (Figure 4). SBP has been also used in the production of fermentation products such as bioethanol and succinic acid (Zheng et al., 2013; Alexandri et al., 2019).

2.5. Spent coffee grounds

Wet processing of coffee cherries involves the removal of husks, peel and pulp followed by roasting, while the coffee extract represents around 5-10 % of the cherry mass and 45-50 % of the cherry mass is finally disposed as spent coffee ground (SCG) (Campos-Vega et al., 2015). Roasted coffee contains 27.5 % of water-soluble compounds and 72.5 % of water insoluble compounds (van Dam and Harmsen, 2010). Thus, around 725 kg of SCG are generated from 1 t of coffee. The SCG production in EU-28 is calculated based on the coffee consumption per country and the water insoluble compounds of coffee. In 2016, more than 1.8 million t of SCG were generated from the consumption of 2.5 million t coffee in EU-28. Germany (387×10^3 t/y), Italy (248×10^3 t/y) and France (244×10^3 t/y) produced more than 48 % of the total SCG produced in EU-28. SCG has poor geographic distribution regarding platform chemical production via fermentation as only three counties, including Germany (ca. 188×10^3 t/y), Italy (ca. 120×10^3 t/y) and France (118×10^3 t/y), are able to provide more than 100,000 t of fermentable sugars per annum. SCG has been considered as feedstock for the production of chlorogenic acid, bioethanol, polyhydroxyalkanoates and carotenoids (Petrik et al., 2014; Obruca et al., 2015; Burniol-Figols et al. 2016).

2.6. Crude glycerol

Crude glycerol is the main by-product of the biodiesel industry that contains 77–90% glycerol, 5.3–14.2% water, up to 1.7% methanol and either 4.2–5.5% NaCl or 0.8–6.6% K_2SO_4 based on the catalyst used (Koutinas et al., 2014). According to EU Biofuels Annual Report (2019), the biodiesel production accounts for 9.8 million t. Around 1 kg of glycerol is produced per 10 kg biodiesel (Quispe et al., 2013), thus around 0.98 million t per year of glycerol are available in EU-28. Crude glycerol has been evaluated as feedstock for the production of various bio-based chemicals and polymers (e.g. succinic acid, poly(3-hydroxybutyrate), microbial oil, butanol, 1,3-propanediol) via fermentation (Vlysidis et al., 2011; Casali et al., 2012; Xu et al., 2012; Salakkam and Webb, 2018; Krasnan et al., 2018).

2.7. Spent liquor from the pulp and paper industry

The thick liquor generated from the pulp and paper industry accounts for approximately 26.4 million t per year in EU-28. For the production of 1 t of pulp with sulphite pulping process, 8-9 m^3 liquid wastes are generated, while the sulphate pulping process generates 7 t of liquid wastes. The generic composition of spent liquors is presented in Table 1. Both liquors have 10 – 20 % solid content and they are processed through multiple evaporation steps to increase their solid content to 60 – 75 %. Spent liquors from the pulp and paper industry are rich in C5 and C6 sugars. The thick liquor contains around 90-200 g/L sugar monomers (Koutinas et al., 2014). It is estimated that the fermentable sugars derived from the spent liquors will be higher than 100,000 t in 8 countries, especially in Sweden (ca. 897×10^3 t/y), Finland (ca. 815×10^3 t/y) and Portugal (ca. 303×10^3 t/y).

Spent liquors from the pulp and paper industry have been evaluated for the production of bioethanol, antioxidant-rich extract, lignosulphonates and succinic acid (Alexandri et al., 2016; Pateraki et al., 2016; Sebastião et al., 2016). Ladakis et al. (2018) has evaluated spent sulphite liquor for the development of continuous cultures for succinic acid production using *Actinobacillus succinogenes* and *Basfia succiniciproducens*.

2.8. Organic fraction of municipal solid wastes

The organic fraction of the municipal solid waste (OFMSW) has been estimated considering around 30 % content in the MSW. The fermentable sugars in OFMSW have been estimated considering 75% moisture content and 45.8% fermentable sugar content in OFMSW (Table 1) based on unpublished data obtained in the PERCAL project (www.percal-project.eu). Thus, the OFMSW is estimated at around 74.4 million t in 2016 in EU-28 (Eurostat, 2016). This amount corresponds to 8.5 million t of potential fermentable sugars. This is the highest fermentable sugar content that can be generated among all the IFSS presented in this critical review. OFMSW has high geographic distribution regarding platform chemical production via fermentation as 16 counties, including Germany (ca. 1,786×10^3 t/y), France (ca. 1,192×10^3 t/y), UK (ca. 1,084×10^3 t/y) and Italy (ca. 1,035×10^3 t/y), will be able to provide more than 100,000 t of fermentable sugars per year. Even if half of the estimated quantities are considered as raw material for biogas and compost production, the remaining quantities are still sufficient for the development of many industrial biorefinery plants for bio-based chemical production via fermentation. Figure 5 presents a potential biorefinery concept based on the PERCAL project that focuses on the valorization of the OFMSW for the production of ethanol, lactic acid and/or succinic acid from the sugar-rich hydrolysate of OFMSW, while the fermentation products and the remaining OFMSW fractions (e.g. protein, lipids/fats) are subsequently used for the production of various end-products (e.g. poly(lactic acid), ethyl lactate, biosurfactants, polyester polyols and polyurethanes).

OFMSW hydrolysates have been used for the production of succinic acid and lactic acid (Babaei et al., 2019; López-Gómez et al. 2019). Individual food supply chain side streams collected at source could be also used for the production of bio-based chemicals and polymers, such as succinic acid production from waste bread (Leung et al. 2012).

2.9. Technologies for the extraction of value-added products via biorefinery development

2.9.1. Bioactive compounds

Lipids, phenolic compounds, flavonoids and other value-added products can be extracted from IFSS. The conventional methods for extraction of bioactive compounds occurs via solid liquid and liquid-liquid extraction. These methods require high amounts of solvents, high energy consumption and there is a risk of thermal degradation (Banerjee et al., 2017). Ethanol is a GRAS solvent and is preferred due to its relatively low boiling point and easy recovery (Banerjee et al., 2017). Novel methods use ionic liquids for the extraction of bioactive compounds. The advantage of ionic liquid utilization is that they can be used to dissolve hydrophilic or hydrophobic molecules at room temperature. Other novel methods that have been used for the extraction of value added products are: i) supercritical fluid extraction, ii) reactive extraction, iii) supercritical carbon dioxide extraction, iv) ultrasound assisted extraction, v) microwave-assisted extraction, v) microwave steam distillation, vi) vacuum microwave hydro-diffusion, vii) enzyme-assisted extraction, viii) pressurized liquid extraction, ix) pulse electric field extraction, x) ionic liquid extraction (Santana-Méridas et al., 2012).

2.9.2. Protein extraction

The most common and widely applied technology for protein isolate production starts with the addition of alkali in order to reach a pH value higher than 9 with NaOH, where neutral and acidic amino acids are ionized resulting in increased water solubility. Solid to liquid ratio, temperature and time are some of the most important factors to optimize the solubility of the proteins. After solubilization, the protein fraction can be recovered via precipitation at the isoelectric point. Utilization of organic solvents for protein solubilization (i.e. ethanol, isopropanol and hexane) and purification (i.e. chloroform) can also be used, while water-solvent or alkaline water-solvent environments can be also effective for protein recovery. Alkaline-ethanol extraction has led to protein recovery up to 90 % from corn distillers' grain (Cookman and Glatz, 2009).

Enzyme utilization could also be applied form protein recovery (e.g. a-amylase, pectinase, cellulase, hemicellulase, xylanase). Peptidases can be used (alone or combined with other enzymes or chemical treatment) for protein hydrolysis and peptide release. The major drawback is the challenging recovery of the low molecular weight peptides (Bandyopadhyay et al., 2012). Other methodologies used for protein extraction are: (i) Ultrasounds-assisted extraction, (ii) Electro-based extraction, (iii) Microwave-assisted extraction, (iv) Screw extrusion, (v) High pressure-assisted extraction (Contreras et al., 2019).

2.9.3. Pectin extraction

The conventional method for pectin extraction involves solid-liquid extraction at temperatures that range from 80 – 100 ^{o}C. Solubilization of protopectin occurs in acidified water at low pH using different acids (e.g. sulfuric, phosphoric, acetic, citric, hydrochloric acid) followed by precipitation with an organic solvent such as ethanol (Bhushan et al., 2008). The degree of extraction depends on the solid-liquid ratio, pH, extraction time and temperature. Novel technologies include ultrasound, microwave and enzyme assisted extraction. During ultrasound assisted extraction, frequencies of 20 – 37 Hz with power that ranges from 130 – 800 W have been used in different fruits with high pectin content. Similar to the conventional method, pectins are extracted in acidified water and low pH at lower temperatures. Extraction yield ranges from 5-30 % depending on numerous factors (substrate, frequency, power, temperature, extraction time and type of acid) (Marić et al., 2018). Microwave assisted extraction occurs at power supply that ranges from 150 – 1200 W for a short period of time (less than 30 min). Extraction yield higher than 30% has been achieved in sugar beet pulp at power supply of 150 – 250 W and extraction time of 2 – 4 min (Marić et al., 2018). Enzyme assisted extraction targets hydrolysis of plant cell walls and involves the utilization of cellulolytic, proteolytic and pectinolytic enzymes. The esterification degree is usually higher in enzyme assisted pectin extraction due to mild processing conditions (Adetunji et al., 2017).

3. Sustainability assessment for the production of bio-based chemicals and polymers

Biorefinery development including the production of bio-based chemicals and polymers from crude renewable resources should lead to sustainable processes and products. In the circular bioeconomy era, sustainability assessment should be employed in order to assess the potential industrial implementation of a biorefinery scenario. The conventional linear production and consumption model relies on continuous growth and increasing resource throughput, while the circular production model will enhance resource efficiency towards minimization of waste disposal and improved balance considering economic, environmental and social aspects (Ghisellini et al., 2016). Circularity will be achieved by choosing the optimal combination of end-of-life (EoL) scenarios. Gargalo et al. (2016) proposed a specific framework for techno-economic and environmental sustainability analysis that can be divided into six steps: problem definition, data collection and management, deterministic techno-economic and environmental analysis, sensitivity analysis, risk quantification and finally risk assessment and decision making. This approach aids in evaluating the alternative processing options leading to the identification of the most sustainable process.

The need to quantify, simplify and communicate scientific information has led to the development of specific indicators which give the opportunity to explain the performance of a process and enable the comparison among alternative technologies considering environmental, economic and social aspects (Singh et al., 2009). For instance, in the case of bioenergy systems, Buchholz et al. (2009a) evaluated 35 sustainability criteria considering relevance, practicality, reliability, and importance attributes with environmental criteria rated as more important and relevant (greenhouse gas balance and energy balance received the highest ratings on all four attributes), economic criteria perceived as more reliable and practical, and social criteria always rated the lowest.

In this section, the most common indicators used in biomass, biofuel, bio-based chemicals, biopolymer and bioenergy production are presented. Moreover, EoL options are reported towards the implementation of circular bioeconomy principles.

3.1. Techno-economic pillar

This pillar includes the assessment of process profitability and the effect of external environmental costs. The estimation of process profitability will start with process design including the development of the process flow sheet and the estimation of material and energy balances. Plant capacity and feedstock requirements are important attributes in this assessment. The main costs that should be determined are the total capital investment (TCI) required to construct the plant and the cost of manufacture (COM) estimated during plant operation. Dheskali et al. (2020) presented a simple and robust mathematical model for the estimation of fixed capital investment and utilities consumption of industrial bioprocesses. The total capital investment, also known as Capital Expenditure (CAPEX), is the sum of the Fixed Capital Investment (FCI) and the working capital. The COM, also known as Annual Expenditure (OPEX), is calculated on an annual basis and based on the methodology proposed by Turton et al. (2018), it could be estimated using equation 1.

$$COM = 0.18 \times FCI + 2.73 \times COL + 1.23 \times (CUT + CRM + CWT) + depreciation \qquad (1)$$

where COL is the cost of operating labor, CUT is the cost of utilities CWT is the cost of waste treatment and CRM is the cost of raw materials.

Profitability assessment of one or alternative processing options is carried out via discounted cash flow analysis considering the TCI, the COM, the plant construction period, the interest rate, the income tax rate, the depreciation method, the plant life, and the construction start-up duration. Finally, sensitivity analysis (e.g. Monte-Carlo simulations) could be carried out for the assessment of variability of process parameters.

The most common literature-cited techno-economic indicators assessing process profitability reported are presented in Table 2. The Net Present Value (NPV) represents the sum of annual present values for the whole plant life time estimated by converting annual cash flows into present values (equation 2).

$$\mathrm{NPV} = \sum_{n=0}^{N} \left[\frac{CF_n}{(1+i)^n}\right] \quad (2)$$

where CFn is the annual cash flow acquired at year n, N is the total number of years corresponding to the analysis period, and i is the annual interest rate.

The Minimum Selling Price (MSP) represents the selling price of the product in which the NPV is equal to zero at the end of the project life time. The Payback Period is the time required, after the initiation of plant operation, to recover the capital investment. The Minimum Feedstock Requirement (MFR) represents the amount of feedstock required to satisfy the plant production capacity considering that the NPV is equal to zero at the end of the project life time (Serna-Loaiza et al. 2018).

Table 3 presents literature-cited indicator values from different processes for the production of bio-based chemicals and polymers. In many cases, the values of indicators are quite variable due to varying plant production capacities and the different production processes employed. Bonatsos et al. (2020) reported the techno-economic and environmental assessment of microbial oil production showing also the dependence between the raw material used and the results of the impact assessment. De Oliveira et al. (2018) reported the MSP for lactic acid production considering various substrates and downstream separation and purification processes.

External economic aspects associated with the manufacturing stage are an important factor that affects the economic feasibility of a process. The term "environmental prices" addresses the welfare expenditure that is associated to the release of 1 kg of any pollutant to the environment (De Bruyn et al., 2018). Consequently, it is necessary to consider the cost of externalities, as in a circular bio-economy context, the production of bio-based chemicals and polymers should be compared with their fossil counterparts. Environmental impacts generally include human health (health and occupational health impacts), human welfare (aesthetic, materials and resource use impacts), environmental resources (biodiversity/endangered species, coastal and other marine ecosystems, groundwater, terrestrial ecosystems impacts), and global systems impacts (global, environmental, physical, psychological, socioeconomic/cultural impacts). Energy and transportation sectors are those with the most developed methodology for the estimation of externalities. The ExternE methodology (Bickel et al., 2004) provides a framework for transforming impacts that are expressed in different units into a common unit, such as monetary values. The external costs are described considering two parameters: an economic parameter representing the accounting price per unit of impact and a physical parameter representing the unit of the impact. The principal stages for the implementation of this methodology are the definition of the activity to be assessed, the definition of the important impact categories and externalities and finally, the estimation of the impacts or effects of the activity (in physical units) by using a Life Cycle Assessment (LCA) methodology. Other similar models observed most frequently in literature are: the Tellus model (Tellus packaging study), the EPS 2000 model (Environmental priority strategies) and the ECON model (Jantzen and Pešic, 2004). The monetization of the estimated impacts is carried out by employing average values of environmental prices considering monetary values for emissions of different pollutants, environmental themes (e.g. climate change) and impacts of environmental pollution (e.g. damage to human health) (De Bruyn et al., 2018).

Economic viability should be also assessed considering macroeconomic sustainability using relevant indicators such as total value added in the economy, trade balances, foreign investments, changes in overall productivity, business opportunities, long-term profitability, energy diversity, product durability and research and development efforts (Azapagic and Perdan, 2000; Buchholz et al., 2009b; Sadamichi et al., 2012; Gargalo et al., 2016; Khishtandar et al., 2017).

3.2. Environmental pillar

LCA is used to assess the environmental impacts which are related to the production of a product. The assessment takes into consideration the entire or part of the product life cycle including raw materials, processing, transportation, use, maintenance and the EoL management after the product use phase (Biron, 2016). The general framework of the LCA is specified in ISO 14040. This framework is separated into four phases, the definition of goal and scope, the inventory analysis, the impact assessment and the interpretation of results. The goal and scope phase defines the temporal, geographic and systemic boundaries, impact categories and related indicators (e.g. GHG emissions, energy demand, land-use, waste-factor), the product's functional unit, assumptions, cut-off criteria and uncertainties from uncontainable factors of the system. The life cycle inventory phase focuses on the collection of data exploiting mass and energy balances along the entire life cycle of the product. Data quality is evaluated during the inventory analysis (Singh et al., 2018). The inventory data collected are employed in the impact assessment phase for the evaluation of environmental impacts (Singh et al., 2018). The relative contribution of each type of emission to impact categories is evaluated. Interpretation is the last LCA phase in which the life cycle inventory and impact assessment are combined in order to reach conclusions and recommendations.

The environmental impact categories commonly used in LCA studies (Weiss et al., 2012; Nessi et al., 2018) are related to non-renewable (or fossil fuel) energy use, climate change, acidification, eutrophication and ozone depletion and formation. The metrics of each environmental impact category refer to the quantitative values based on specific and representative equivalents for each of them. Global warming potential expresses the impact of each greenhouse gas on global warming using carbon dioxide (kg CO_2-eq per functional unit) as the refence gas complying with the guidelines of the Intergovernmental Panel on Climate Change (Durkee, 2006). The non-renewable (or fossil fuel) energy use, expressed as MJ of non-renewable energy use per functional unit, is the impact category which is related to the depletion of non-renewable resources (Azapagic et al., 2003). The acidification potential, expressed as SO_2 equivalents per functional unit, describes the negative impact of acidifying pollutants (e.g. SO_2, NOx) on soil, ecosystems, ground and surface water, surface water and materials (Biron, 2016). The eutrophication potential, expressed as PO_4-equivalents per functional unit, describes excessive nutrient input into soil and water via fertilization, effluent disposal and combustion processes (Nixon, 1995; Azapagic et al., 2003; Smith, 2003). The human toxicity potential, expressed as 1,4-dichlorobenzene equivalents per functional unit, describes the factors that cause toxicological impacts to humans (Azapagic et al., 2003). The Particulate Matter Formation impact category describes the harmful effect on human health caused by emissions of particulate matter and its precursors (e.g. NO_x, SO_x, NH_3) (Nessi et al., 2018).

Nessi et al. (2018) presented impact categories, indicators and related impact assessment methodologies that should be applied in an LCA study. Table 3 presents representative indicators and values that have been estimated from various bioprocesses for the production of bio-based chemicals and polymers using various renewable raw materials. Global warming potential and fossil energy consumption are the most frequently used indicators. The wide variation of the global warming potential values occurs due to the production process and the feedstock employed. For instance, the downstream separation and purification method for succinic acid followed by González-García et al. (2018) requires large amounts of solvents and electricity, a fact that increases the total environmental impact on both global warming potential and fossil energy consumption categories.

Besides individual bioprocesses, the environmental impact of waste refining or management has also been assessed. Joglekar et al. (2019) evaluated the environmental performance of a citrus waste biorefinery including hydrolysis, filtration, fermentation and distillation for the production of ethanol, while the solids remaining after filtration are employed for methane production via anaerobic digestion. Global warming potential is 0.4 kg CO_2-eq per kg of citrus waste, the acidification potential is 3.4 g SO_2-eq per kg of citrus waste and the eutrophication potential is 0.2 g PO_4^{3-}-eq per kg of citrus waste. Slorach et al. (2019) compare four different management practices for the treatment of food wastes. Anaerobic digestion indicated the lowest environmental impacts per t of waste in most of the categories considered in the study, having also a net-negative global warming potential.

3.3. Social pillar

Socioeconomic indicators focus on the evaluation of the human well-being as related to industrial operation in a specific region. Health and safety, job creation and satisfaction and social justice issues are some of the social aspects assessed by such indicators. There is a wide variation in the social indicators and their units identified in literature-cited studies (Kooduvalli et al., 2019). Social indicators quantify social impacts (midpoint and endpoint: describing the points of impact along the pathway of a system) that can affect people's working conditions locally, and to show impacts on a larger community level (Jørgensen et al., 2008). Along similar lines, Dreyer et al. (2006) has presented a framework for social assessment that deals with the entire life cycle of a product with emphasis given on the stages where the company has the largest influence, the materials and product manufacturing stages.

Dale and Beyeler (2001) presented a literature review presenting the key criteria for the selection of social indicators. The selected indicators should be easily, timely and cost-effectively measured. Moreover, the method of implementation and the final responses of the indicators should be unambiguous. The set of the selected indicators should be sufficient when considered collectively in order to reach a representative outcome. Indicators meeting these criteria should allow users to set targets and select the most sustainable processes (Dale et al., 2013). Table 4 presents the most common categories evaluated in social assessment and the most representative indicators in each category.

3.4. End-of-Life options – Implementation of circular bioeconomy principles

Efficient waste management and EoL options are crucial factors influencing the development of a resource efficient life cycle in the case of bio-based products. The current linear economic model does not pay attention to recirculation option of used products. According to the Ellen MacArthur Foundation, circular bioeconomy is a "continuous, positive development cycle that aims to keep products, components, and materials at their highest utility and value at all times". In this section, the different EoL options are presented and their contribution in circular value chains is briefly discussed.

3.4.1. Reuse

The most effective way to reduce waste is the reuse of materials and products. This option is the most effective so as to reduce the consumption of natural resources and the generation of waste streams in an economic manner. Moreover, the environmental impact can also be reduced.

3.4.2. Mechanical recycling

Mechanical recycling is a method by which waste materials are recycled into secondary raw materials without changing the basic structure of the material. Mechanical recycling of plastics involves mainly size reduction (e.g. grinding), sorting and reprocessing by conventional processing technologies (Resch-Fauster et al., 2017). The recyclates derived after mechanical recycling of plastic waste are pellets, granules or flakes among others.

Non-biodegradable bio-based plastic waste, such as bio-based polyethylene, can be easily managed through mechanical recycling together with their fossil counterparts as they are chemically identical (European Bioplastics, 2015). Mechanical recycling could be also applied in the case of bio-based and biodegradable plastics, such as PLA (De Andrade et al., 2016). It should be stressed though that the mechanical properties of the recyclate should be similar to the originally produced plastic material. Mechanical recycling presents low environmental impact followed by chemical recycling and composting.

3.4.3. Chemical recycling

During chemical recycling, plastic polymers are broken down into their monomer components. The recovered monomers can be used in biorefineries for the production of bio-based chemicals and polymers. Research has focused on the development of chemical recycling of PLA (De Andrade et al., 2016).

3.4.4. Composting & anaerobic digestion

Bio-based products that cannot be processed via mechanical or chemical recycling, could be processed via composting or anaerobic digestion for biogas production. The biodegradable/compostable polymers are degraded into water, carbon dioxide, humus and inorganic compounds in the aerobic biodegradation process, while methane is also produced in the anaerobic biodegradation process (Resch-Fauster et al., 2017). The produced biogas can be used for the co-production of electricity and heat.

3.4.5. Energy recovery - incineration

The potential treatment of used bio-based products for energy recovery is considered by European Bioplastics (2017) as an alternative EoL option, when the other methods cannot be implemented. This option provides renewable energy. Non-biodegradable and non-recyclable bio-based materials should be valorized for energy recovery.

3.4.6. Landfilling

This is an option among the alternative EoL routes for bio-based products that should be avoided. Besides potential health hazards, this option can cause fires and explosions, vegetation damage, unpleasant odors, landfill settlement, ground water pollution, air pollution and global warming (El-Fadel et al., 1997).

4. Case study - Techno-economic evaluation of succinic acid production

Spekreijse et al. (2019) presented an insight into the European market for bio-based chemicals. Succinic acid has been considered as an important platform chemical in the bio-economy era, but its high prospects did not lead to high industrial production due to the high production cost (2.94 $/kg) and the low market demand. The most common carbon source utilized in current industrial fermentations for succinic acid production is mainly glucose syrup from corn. The development of integrated biorefineries using IFSS could lead to sustainable production of succinic acid. The exploitation of IFSS for the production of succinic acid should be evaluated via sustainability assessment focusing on the selection of appropriate indicators. Both the cost and the environmental impact of the production process are highly affected by the selection of the raw material, the pretreatment stage, the fermentation stage, as well as the downstream separation and purification of succinic acid. Sustainability assessment should take into consideration feedstock availability and geographic distribution, techno-economic evaluation, as well as environmental and social impact.

This section presents a case study on the techno-economic evaluation of succinic acid production using the organic fraction of municipal solid waste as feedstock. The profitability of bio-based succinic acid production has been evaluated using 5 indicators (i.e. NPV, MSP, COM, MFR and payback period). The bioprocess is divided into feedstock pretreatment, fermentation and downstream separation and purification stages. Feedstock pretreatment is represented in this assessment by varying the production cost of fermentable sugars in order to present the profitability margin of this process.

The fermentation stage includes the preparation and sterilization of fermentation media as well as bioreactor operation. The number, volume and scheduling of bioreactors has been estimated according to the methodology presented by Dheskali et al. (2017). The fermentation process is simulated using experimental results achieved in lab-scale bioreactors using *A. succinogenes* cultivated on OFMSW hydrolysate (unpublished data). The final succinic acid concentration is 29.4 g/L with a sugar to succinic acid conversion yield of 0.56 g_{SA}/g_{sugars}. The fermentation duration is 33 h. Carbon dioxide supply is used during fermentation. The inoculation stream is 10% (v/v) of the fermentation volume.

The downstream separation and purification of succinic acid used in this case study has been presented by Alexandri et al. (2019). The fermentation broth is initially centrifuged to remove the bacterial biomass. Treatment in active carbon columns is subsequently carried out for decolorization and impurity removal. Acidification of succinate salts is carried out via ion exchange resin columns, which are regenerated using 5 % HCl aqueous solution. The acidified liquid stream is concentrated using a mechanical vapor recompression forced circulation evaporator system. The concentrated liquid is fed into continuous crystallizers and the wet succinic acid crystals are dried in a spray dryer.

Preliminary techno-economic analysis has been carried out considering 8300 h per year of plant operation. The fixed capital investment is estimated by considering mainly the purchased equipment cost. The purchased equipment cost, fixed capital investment and cost of manufacture have been estimated using the methodology reported by Koutinas et al. (2016). Equipment sizing is performed using well known chemical engineering procedures and rules of thumb (Peters et al., 2003; Ulrich and Vasudevan, 2004, Turton et al., 2018). The cost of manufacture is estimated using equation 2. A discounted cash flow analysis is carried out based on the current market price of succinic acid (2.94 $/kg). The assumption for performing the DCF analysis is based on the 2011 NREL bioethanol production report (Humbird et al., 2011).

Figure 6 presents the COM, MSP, NPV, payback period and minimum feedstock (OFMSW) requirement for three OFMSW-derived sugar production costs as a function of annual production capacity. The COM and MSP are reduced significantly from 5,000 t to 40,000 t annual production capacity, while at higher annual production capacities the COM and MSP are almost constant. The COM ranges from 2.11 $/kg to 2.45 $/kg at decreasing OFMSW-derived sugar production costs and production capacities higher than 40,000 t. Similarly, the MSP ranges from 2.55 $/kg to 2.84 $/kg. The selection of OFMSW as feedstock for succinic acid production would be a promising option if the production cost of OFMSW-derived sugars is lower than 100 $/t. The payback period (Figure 6d) has been estimated considering 100 $/t (13 years) and 50 $/t (11 years) of OFMSW-derived sugars production cost at annual production capacities of 40,000 t. Figure 6e presents the minimum OFMSW requirements for varying succinic acid production capacities. The OFMSW presented in Figure 6e is considered on wet basis (75 % moisture content).

Conclusions

Biorefinery and bioprocess development for the production of bio-based chemicals and polymers should be based on sustainability assessment considering feedstock availability as well as techno-economic, environmental and social impacts. This should be compared with the fossil-derived counterparts. This study presented feedstock availability focusing on IFSS and reviewed the indicators that should be taken into consideration for sustainability assessment. Circular principles should be also evaluated considering the appropriate selection of EoL scenarios. The case study on succinic acid production showed an example of techno-economic assessment focusing on profitability assessment and minimum feedstock requirement analysis.

Supplementary data

Information on the geographic distribution of fermentable sugars derived from IFSS is provided as e-supplementary data and can be found in the e-version of this paper online.

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Table 1. Composition (% on a dry basis) of the evaluated IFSS

	Grape Pomace	**Grape stalks**	**Wine lees**	**Brewer's Spent Grains**	**Sugar Beet Pulp**	**Orange peels**	**Apple pomace**	**Spent Coffee Grounds**	**OFMSW**	**Spent liquors [2]**
Moisture (%)	75	50	63 [1]	75	7	80	80	65	75	-
Soluble sugars	2.7-12.3	-	-	-	7.1	22.9	10.8 – 15.0	-	0.7–7.4	9.0-20.0
Cellulose	14.5-20.8	25.3-36.3	-	16.8 - 26.0	23.0	22.0	7.2 – 43.6	8.6-13.3	8.5–15.4	-
Hemicellulose	10.3-12.5	13.9-35.3	-	19.2 - 41.9	19.5	11.2	4.3 – 24.4	30.0-40.0	4.2-11.5	-
Lignin	17.2-22.4	17.4-40.6	-	11.9- 27.8	2.6	2.2	15.3 – 23.5	25.0-33.0	5.6-12.1	30.0-45.0
Pectin	5.4-6.2	-	-	-	30.3	25.0	3.5 – 14.3	-	-	-
Starch	-	-	-	-	-	-	-	-	14.2-22.1	-
Phenolics	-	-	2.5	1.0-2.0	1.0	-	-	2.5	-	1.0-2.0 (dry solids)
Tannins	13.8-26.8	6.4-15.9	-	-	-	-	-	-	-	-
Proteins	11.6-18.8	-	10.4	15.3 - 24.7	9.6	6.1	2.9 – 5.7	6.7-13.6	7.0-11.8	-
Fat/Lipids	6.9-13.5	-	1.2	3.0 – 13.0	-	-	1.2 – 3.9	10.0-20.0	1.5-11.5	-
Acetic acid	-	-	-	-	-	-	-	-	-	0.3-0.7
Ash	5.5-9.2	3.9-7.7	5.8	1.1 - 4.6	-	3.7	2.0 – 3.0	-	5.7-25.0	-
Tartrate salts	-	-	20.7	-	-	-	-	-	-	-
Limonene	-	-	-	-	-	3.8	-	-	-	-
References	Galanakis, 2017	Galanakis, 2017	Kopsahelis et al., 2018	Mussatto, 2014; Lynch et al., 2016	Alexandri et al., 2019	Pourbafrani et al., 2010	Dhillon et al., 2013	Obruca et al., 2015	Unpublished data	Koutinas et al., 2014

[1] 63% water and 5.7% ethanol content in 100 g wine lees; [2] generic composition of spent liquors produced by the pulp and paper industry

Table 2. Techno-economic indicators representing process profitability

Indicators	Units	Succinic acid	1,4-BDO	2,3-BDO	Lactic acid	Microbial oil	PLA
Cost of manufacture	$\$/kg_{product}$	0.88 – 2.32	-	2.70 – 3.26	1.07	4.24	3.56
Fixed capital investment	$\$/kg_{product}$	2.88 – 16.75	-	1.29 – 3.36	3.87	2.73	10.97
Net present value	million $	99.00	-	-	234.80	-	202.10
Minimum selling price	$\$/kg_{product}$	0.99 – 2.26	1.82	1.56 – 5.10	0.56 – 5.00	0.72 – 5.8	3.33
Payback period	years	-	-	-	5.10	-	6.60
Gross profit	$\$/kg_{product}$	-	-	-	1.06	-	2.26
Net profit	$\$/kg_{product}$	-	-	-	0.89	-	1.89
References		Efe et al., 2013; Klein et al., 2017; Ghayur et al., 2019	Satam et al., 2019	Koutinas et al., 2016; Maina et al., 2019	De Oliveira et al., 2018; Kwan et al., 2018	Bonatsos et al., 2020	Kwan et al., 2018

Table 3. Environmental indicators

Indicators	Units	Succinic acid	1,4-BDO	Lactic acid	Microbial oil	PLA	PHB
Global warming potential	$kg_{CO2\text{-}eq.}/kg_{product}$	-0.20 – 5.30	1.60 – 3.00	-0.60 – 1.20	2.9 – 11.6	0.30 – 3.20	-2.58 – 3.95
Acidification potential	$kg_{SO2\text{-}eq.}/kg_{product}$	0.73	0.01	-	0.004 – 0.043	$7.0\ 10^{-3}$ – $3.8\ 10^{-2}$	0.022 – 0.028
Eutrophication potential	$kg_{PO4,eq.}/kg_{product}$	0.17	-	-	0.005 – 0.045	$1.8\ 10^{-4}$ – $7.5\ 10^{-3}$	-
Fresh water/ aquatic eutrophication potential	$kg_{P\text{-}eq.}/kg_{product}$	-	9.1×10^{-5}	-	-	0.80 – 1.40	$2.8\ 10^{-3}$ – $11\ 10^{-3}$
Marine eutrophication	$kg_{N\text{-}eq.}/kg_{product}$	-	4.0×10^{-4}	-	-	-	-
Fossil fuel energy use	$MJ./kg_{product}$	6.89 – 227.00	41.50	9.00 – 120.00	-	21.40 – 45.30	-28.39 – 75.97
Particulate Matter Formation	$kg_{PM10\text{-}eq.}/kg_{product}$	-	2.2×10^{-3}	-	-	-	-
Ozone depletion potential	$kg_{CFC\text{-}11\ eq.}/kg_{product}$	13.60	2.1×10^{-7}	-	-	4.0×10^{-10} – 3.6×10^{-7}	-
Human toxicity potential	$kg_{1,4\text{-}DB\ eq.}./kg_{product}$	-	-	-	-	8.5×10^{-3}	-
Photochemical oxidant formation	$kg_{NMVOC.}/kg_{product}$	-	3.5×10^{-3}	-	-	-	-
References		Moussa et al., 2016; González-García et al., 2018; Cok et al., 2014; Dunn et al., 2015; De Matos et al., 2015	Forte et al., 2016; Dunn et al., 2015	De Matos et al., 2015; Morales et al., 2015	Bonatsos et al., 2020	Broeren et al., 2017; De Matos et al., 2015	Kookos et al., 2019

Table 4. Social categories with associated indicators and units for biobased product manufacturing

Category	Indicator	Reference
Human rights/ Equality	Income inequalities	van Haaster et al., 2017; Sureau et al., 2018; Kooduvalli et al., 2019
	Gender equity	Ekener-Petersen et al., 2014; Sureau et al., 2018; Kooduvalli et al., 2019
Human health	Occupational Health	Blok et al., 2013
	Environmental Human Health	Blok et al., 2013
Autonomy	Child Labor	van Haaster et al., 2017; Blok et al., 2013
	Forced Labor	van Haaster et al., 2017; Blok et al., 2013
Safety, security and tranquility	Total employment	Dale et al., 2013; Kooduvalli et al., 2019; van Haaster et al., 2017, Fontes et al., 2018; Blok et al., 2013
	Work days lost due to injury	Dale et al., 2013; Ekener-Petersen et al., 2014; Kooduvalli et al., 2019
Social acceptability	Public opinion	Dale et al., 2013; Kooduvalli et al., 2019
	Transparency	Dale et al., 2013; Kooduvalli et al., 2019
	Stakeholder participation	Dale et al., 2013; Kooduvalli et al., 2019; van Haaster et al., 2017; Blok et al., 2013

Figure legends

Figure 1 Biorefinery development for the extraction of value-added fractions and the production of fermentable sugars from orange peels. The quantities have been estimated using average contents based on the composition range presented in Table 1. The total orange peel quantity is presented in wet basis and the components in dry basis.

Figure 2 Biorefinery development for the extraction of value-added fractions and the production of fermentable sugars from BSG. The quantities have been estimated using average contents based on the composition range presented in Table 1. The total BSG quantity is presented in wet basis and the components in dry basis.

Figure 3 Biorefinery development for the extraction of value-added fractions and the production of fermentable sugars from grape pomace, stalks and wine lees. The quantities have been estimated using average contents based on the composition range presented in Table 1. The winery waste quantities are presented in wet basis and the components in dry basis.

Figure 4 Biorefinery development for the extraction of value-added fractions and the production of fermentable sugars from SBP. The quantities have been estimated using average contents based on the composition range presented in Table 1. The total SBP quantity is presented in wet basis and the components in dry basis.

Figure 5 Biorefinery development for the production of bio-based products from OFMSW developed in the PERCAL project (www.percal-project.eu). The quantities have been estimated using average contents based on the composition range presented in Table 1. The total OFMSW quantity is presented in wet basis and the components in dry basis.

Figure 6 COM (a), MSP (b), NPV (c) estimated for different OFMSW-derived sugar production costs as function of annual succinic acid production capacity. Payback period estimation considering the NPV change during plant operation for different OFMSW-derived sugar production costs (d). Minimum OFMSW requirement (MFR) for the production of different annual succinic acid production capacities (e). OFMSW derived sugars production cost of 50 \$/t (▲), 100 \$/t (Δ), and 200 \$/t (□)

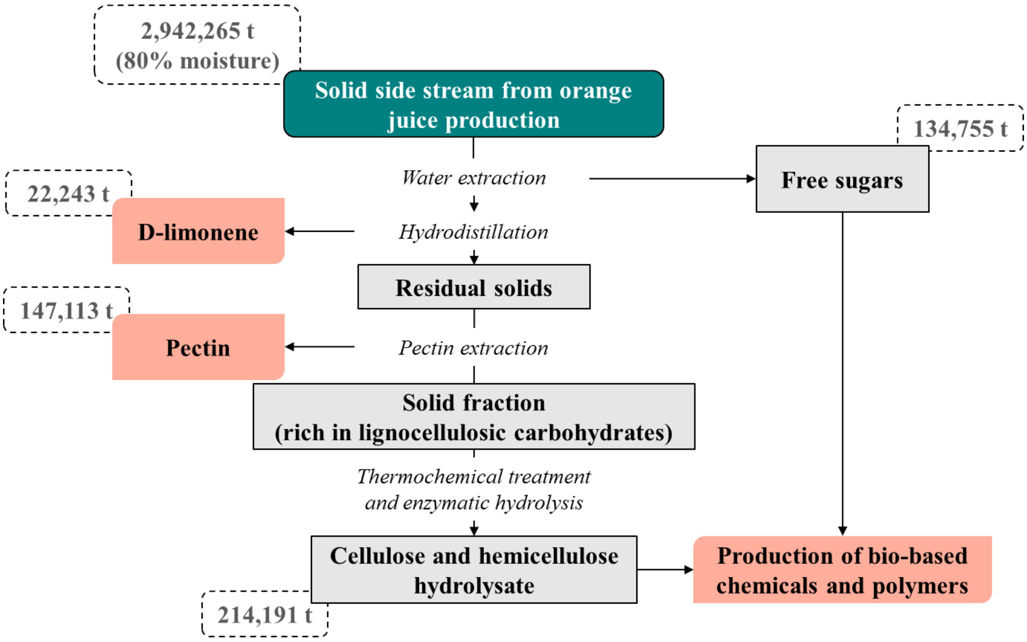


Figure 1

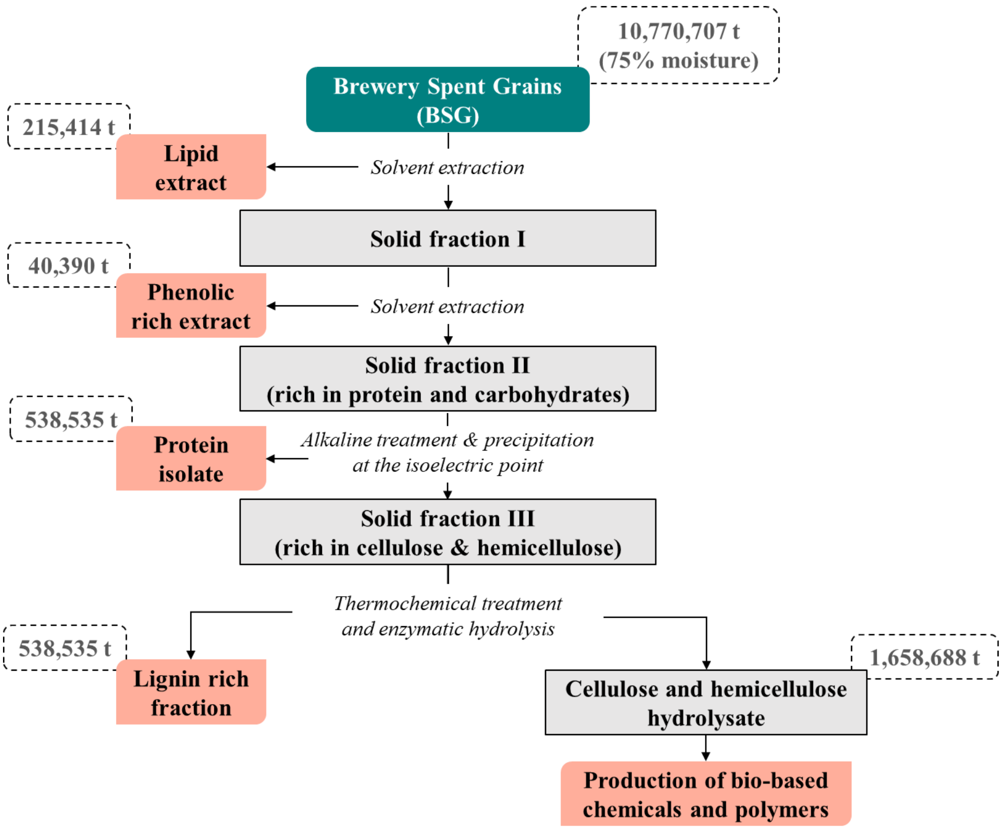


Figure 2

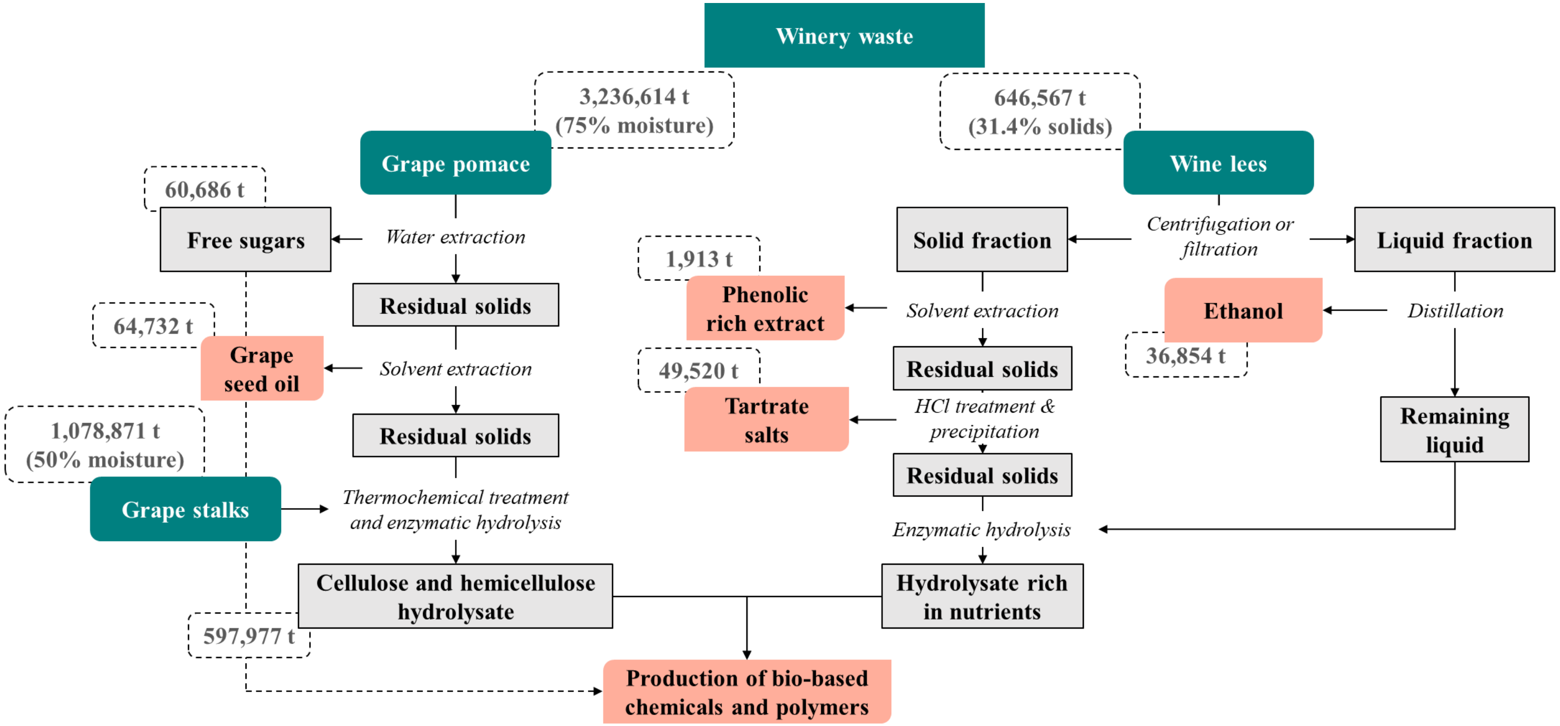

Winery waste
3,236,614 t
(75% moisture)
646,567 t
(31.4% solids)
Grape pomace
Wine lees
60,686 t
Free sugars
Water extraction
Residual solids
64,732 t
Grape seed oil
Solvent extraction
Residual solids
1,078,871 t
(50% moisture)
Grape stalks
Thermochemical treatment and enzymatic hydrolysis
Cellulose and hemicellulose hydrolysate
597,977 t
1,913 t
Phenolic rich extract
49,520 t
Tartrate salts
Solid fraction
Centrifugation or filtration
Liquid fraction
Solvent extraction
Residual solids
HCl treatment & precipitation
Residual solids
Enzymatic hydrolysis
Hydrolysate rich in nutrients
Ethanol
36,854 t
Distillation
Remaining liquid
Production of bio-based chemicals and polymers

Figure 3

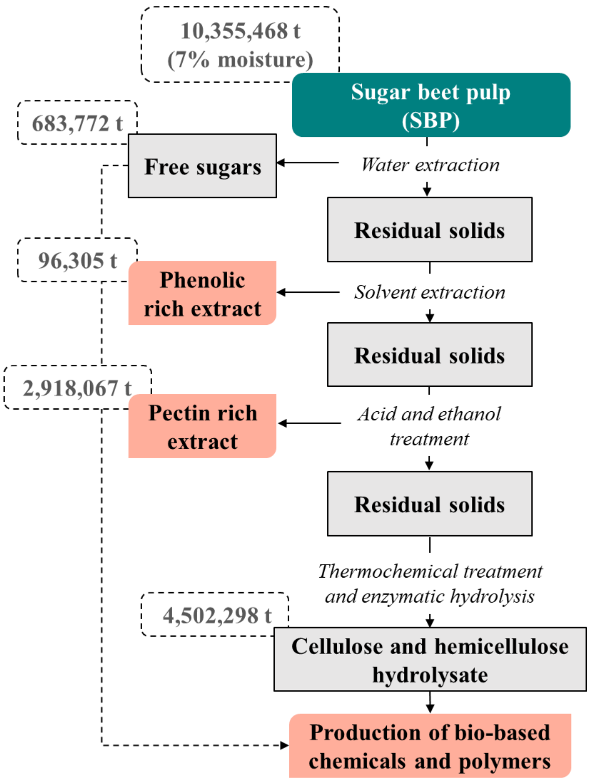


Figure 4

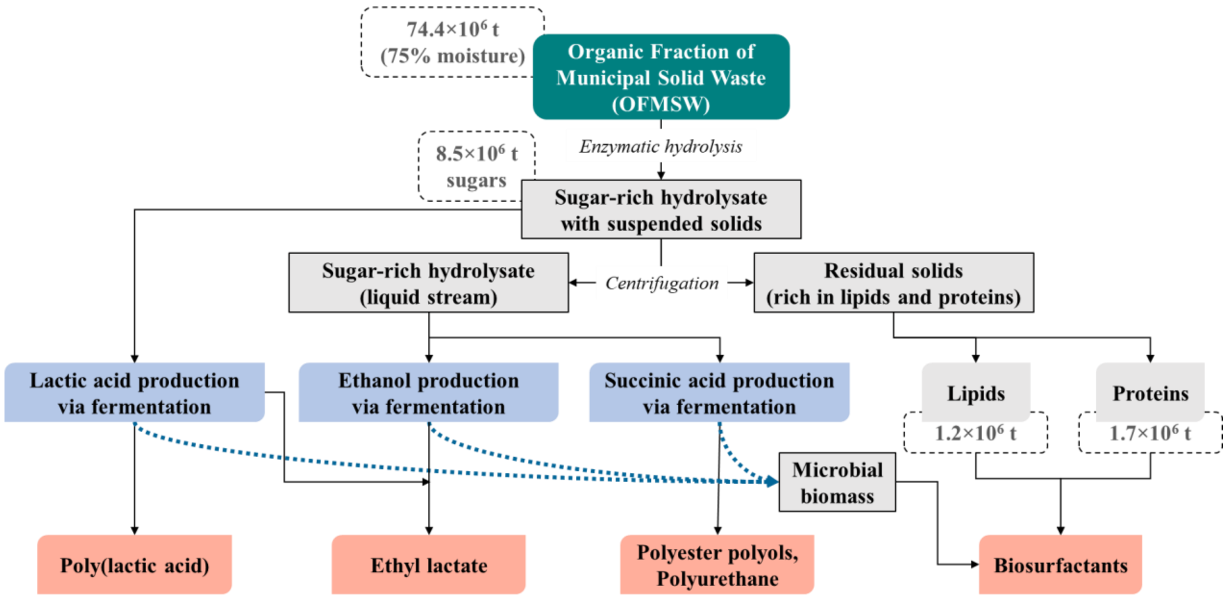


Figure 5

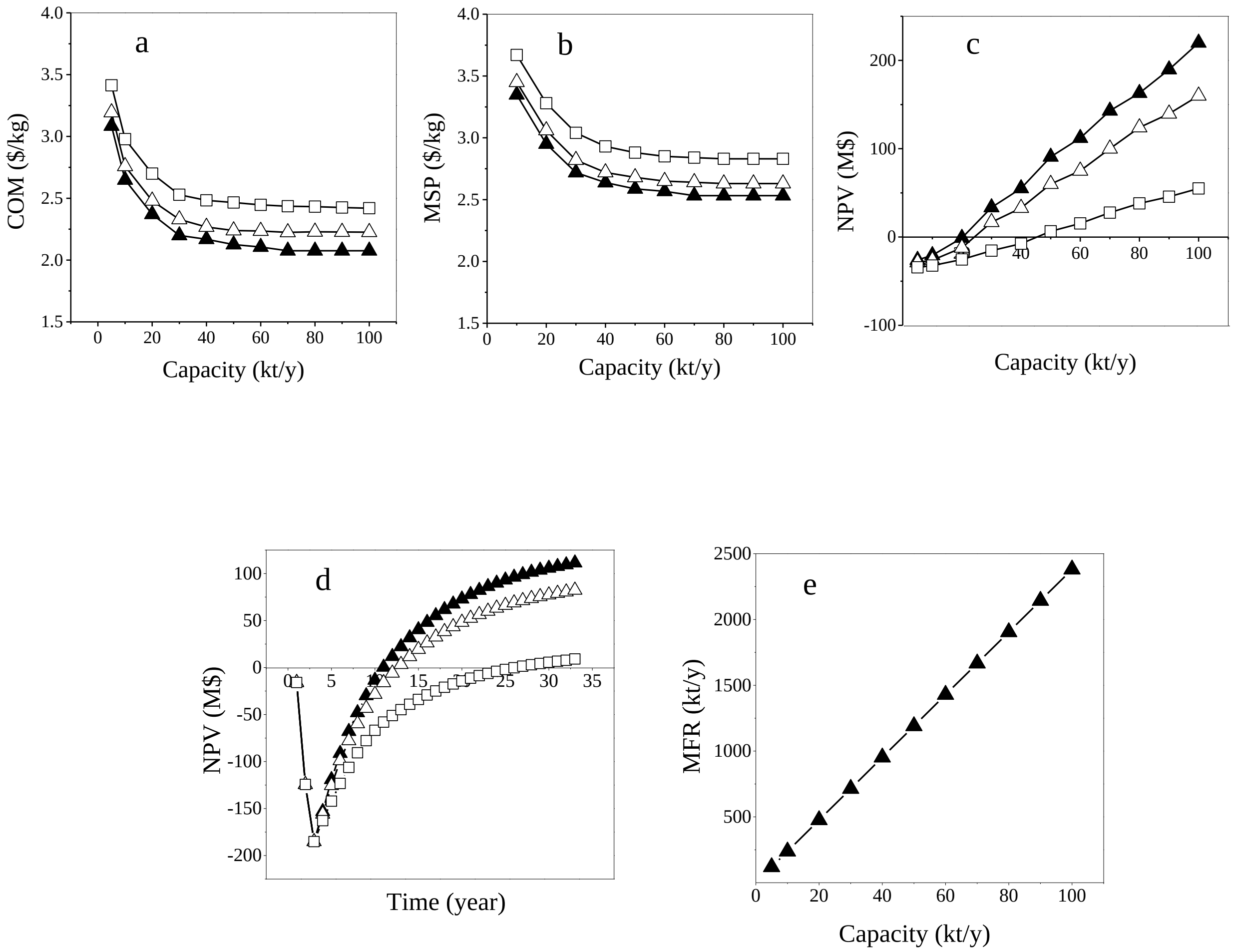

a
COM ($/kg)
Capacity (kt/y)
b
MSP ($/kg)
Capacity (kt/y)
c
NPV (M$)
Capacity (kt/y)
d
NPV (M$)
Time (year)
e
MFR (kt/y)
Capacity (kt/y)

Figure 6

Figure 1 Click here to access/download;Figure;Figure 1.jpg

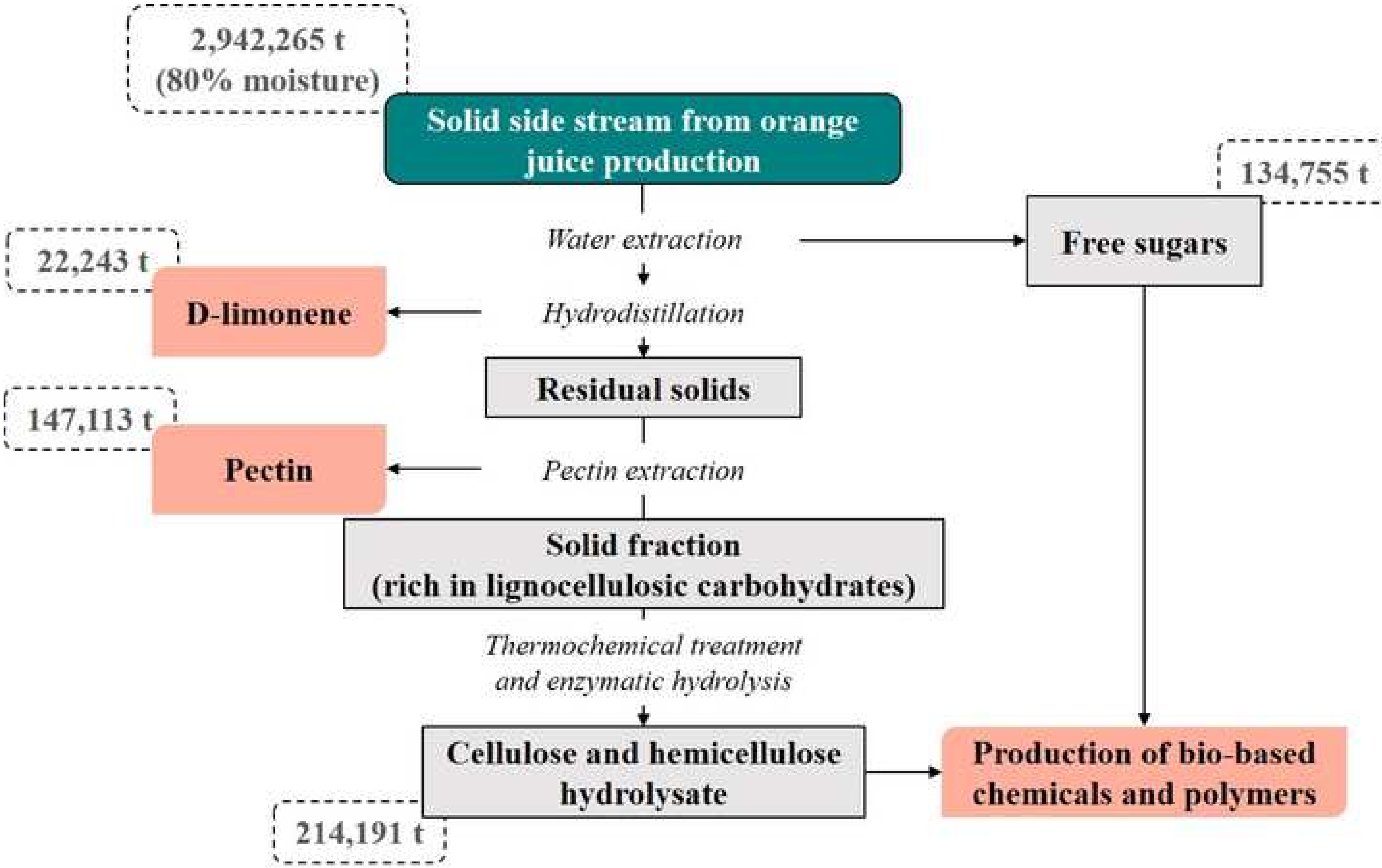


Figure 2

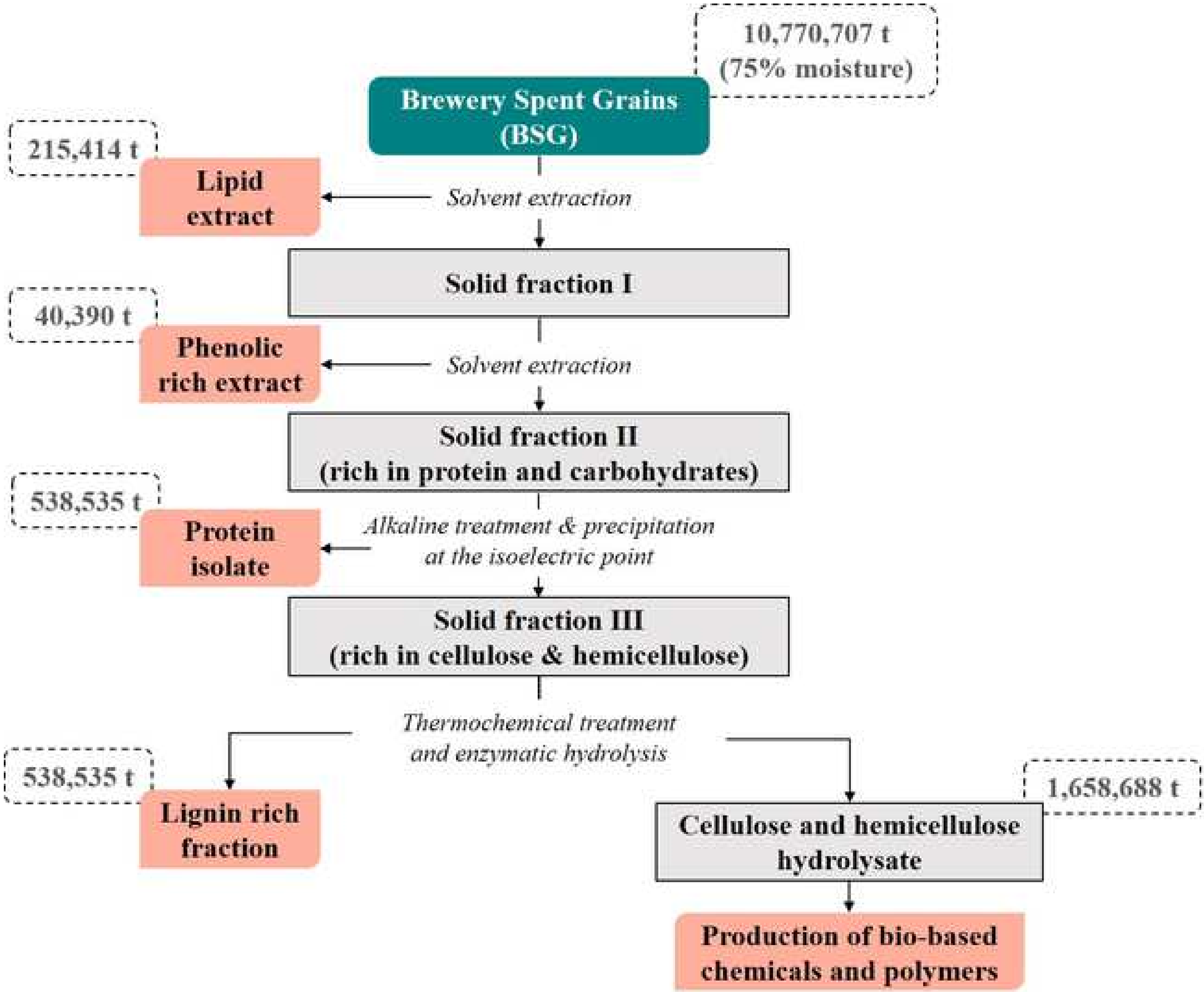

10,770,707 t
(75% moisture)
Brewery Spent Grains
(BSG)
215,414 t
Lipid
extract
Solvent extraction
Solid fraction I
40,390 t
Phenolic
rich extract
Solvent extraction
Solid fraction II
(rich in protein and carbohydrates)
538,535 t
Protein
isolate
Alkaline treatment & precipitation
at the isoelectric point
Solid fraction III
(rich in cellulose & hemicellulose)
Thermochemical treatment
and enzymatic hydrolysis
538,535 t
Lignin rich
fraction
1,658,688 t
Cellulose and hemicellulose
hydrolysate
Production of bio-based
chemicals and polymers

Figure 3

Click here to access/download;Figure;Figure 3.jpg

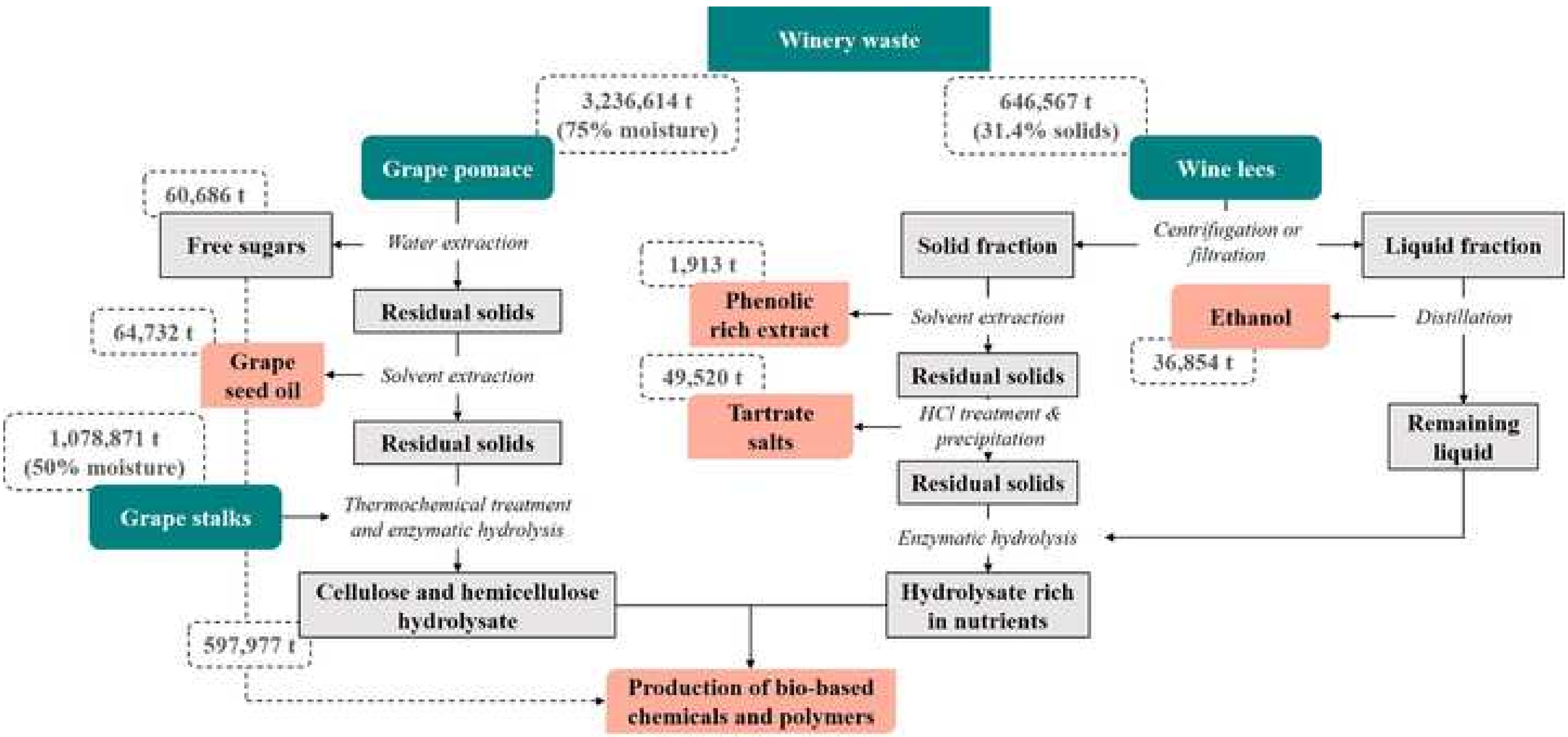


Figure 4

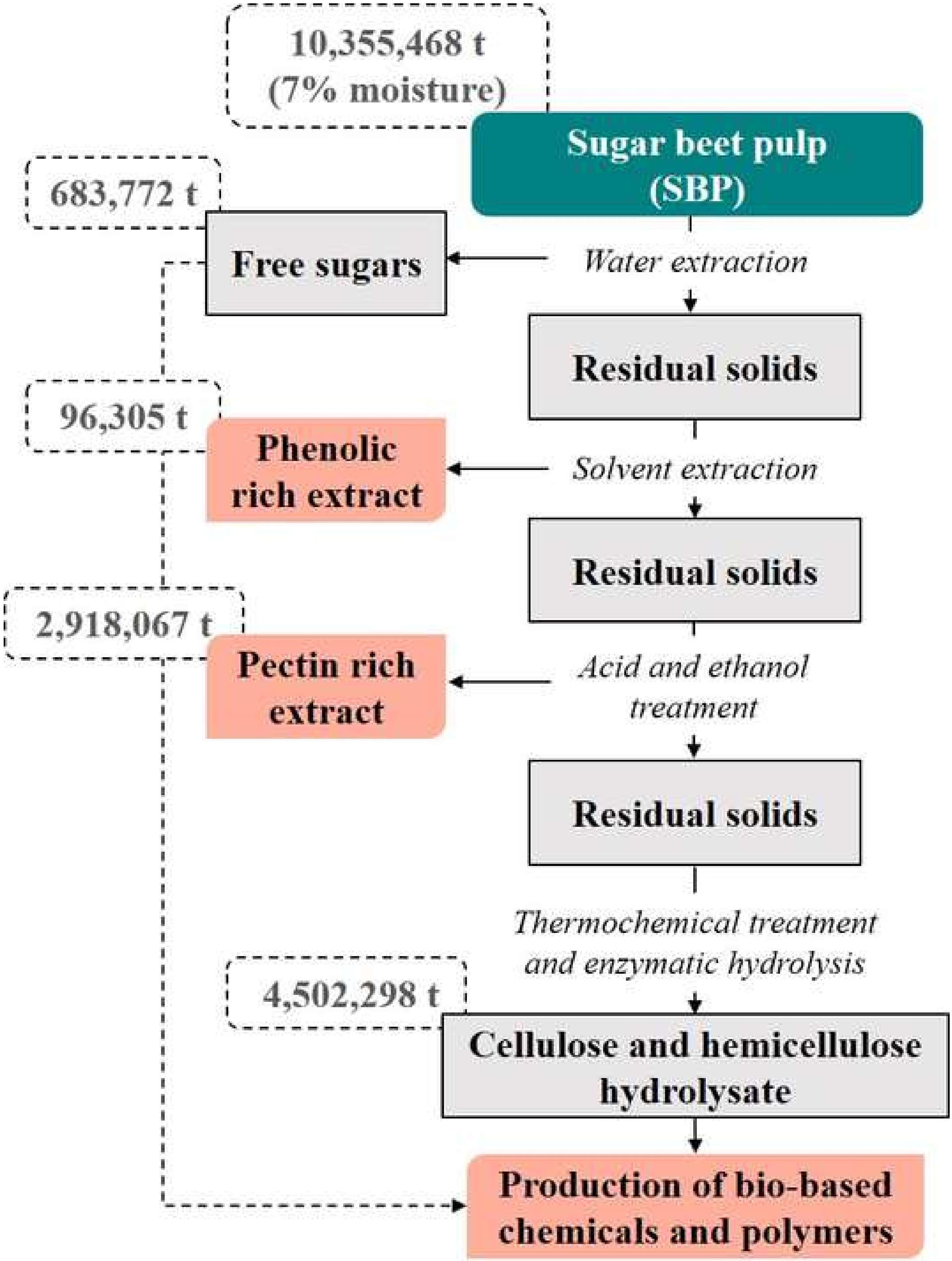
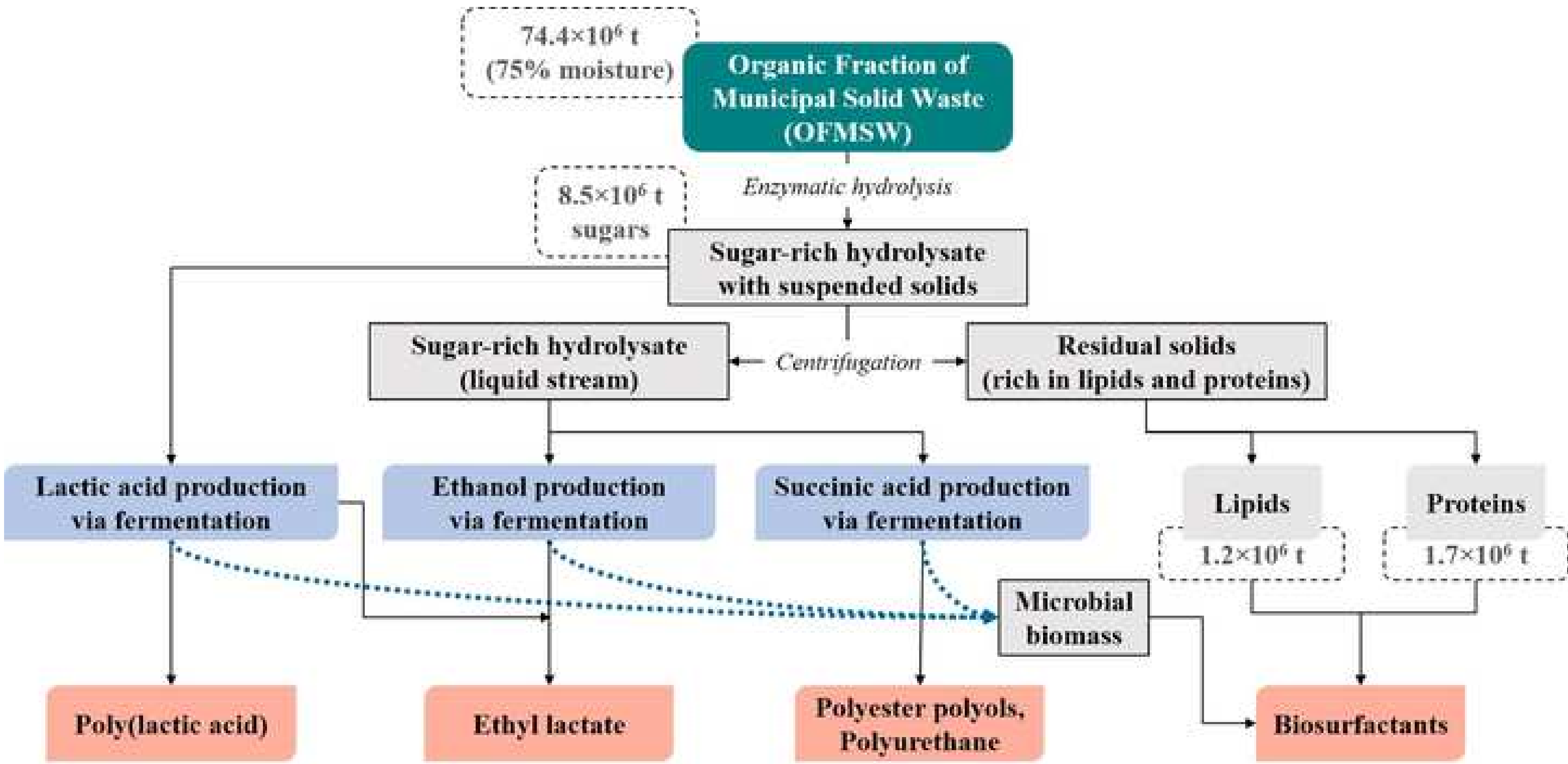

10,355,468 t
(7% moisture)
Sugar beet pulp
(SBP)
683,772 t
Free sugars
Water extraction
Residual solids
96,305 t
Phenolic
rich extract
Solvent extraction
Residual solids
2,918,067 t
Pectin rich
extract
Acid and ethanol
treatment
Residual solids
Thermochemical treatment
and enzymatic hydrolysis
4,502,298 t
Cellulose and hemicellulose
hydrolysate
Production of bio-based
chemicals and polymers

Figure 5


74.4×10⁶ t
(75% moisture)
Organic Fraction of Municipal Solid Waste (OFMSW)
Enzymatic hydrolysis
8.5×10⁶ t sugars
Sugar-rich hydrolysate with suspended solids
Sugar-rich hydrolysate (liquid stream)
Centrifugation
Residual solids (rich in lipids and proteins)
Lactic acid production via fermentation
Ethanol production via fermentation
Succinic acid production via fermentation
Lipids
1.2×10⁶ t
Proteins
1.7×10⁶ t
Microbial biomass
Poly(lactic acid)
Ethyl lactate
Polyester polyols, Polyurethane
Biosurfactants