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Upgrading wineries to biorefineries within a Circular Economy perspective: An Italian case study

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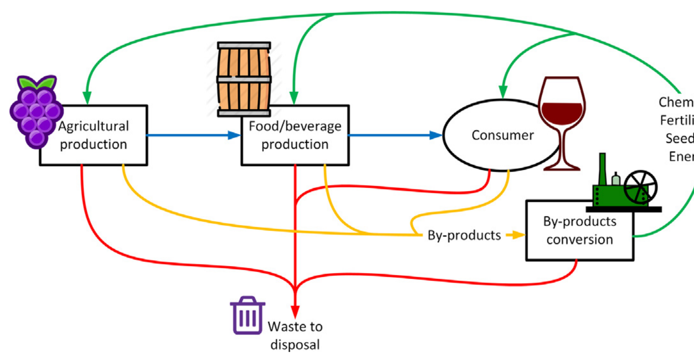
HIGHLIGHTS

- The traditional production of wine is assessed through Life Cycle Assessment (LCA).
- Side chains and circular patterns are integrated in the linear production chain.
- The potentiality of a biorefinery system based on winery waste is explored.
- Environmental benefits are achieved by implementing the circular approach.
- Wine industry can become a proactive model for the whole food industry.

GRAPHICAL ABSTRACT



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ABSTRACT

In the challenge of transforming waste into useful products that can be re-used in a circular perspective, Italian wine industry can represent a suitable model for the application of the bioeconomy principles, including the valorisation of the agricultural and food waste. In the present study, a comprehensive environmental assessment of the traditional production of wine was performed and the potentiality of a biorefinery system, based on winery waste and aimed at recovering useful bio-based products, such as grapeseed oil and calcium tartrate, was examined through Life Cycle Assessment (LCA). The wine company "I Borboni", producing Asprinio wine in the Campania Region (Italy), was proposed as a case study. The hotspots of the linear production system were identified and the bottling phase, in particular the production of packaging glass, resulted to contribute to the generation of impacts at 63%, on average, *versus* 14.3% of the agricultural phase and 22.7% of the vinification phase. The LCA results indicated human carcinogenic toxicity, freshwater eutrophication and fossil resource scarcity impact categories as the most affected ones, with normalized impacts amounting to 9.22E−03, 3.89E−04 and 2.64E−04, respectively. Two side production chains (grapeseed oil and tartrate production) were included and circular patterns were designed and introduced in the traditional production chain with the aim of valorising the winery

Abbreviations: BAU, Business as Usual; CE, Circular Economy; CP-A, circular production option A; CP-B, circular production option B; DOP, protected designation of origin; FAE, fatty acid ethyl ester; FAO, Food and Agriculture Organization; FEP, freshwater eutrophication potential; FRS, fossil resource scarcity; FU, Functional Unit; GDP, Gross Domestic Product; GWP, global warming; HHV, Higher Heating Value; LCA, Life Cycle Assessment; HTP_{cn}, human carcinogenic toxicity; ISO, International Standards Organisation; ISTAT, Italian National Institute of Statistics; MEP, marine eutrophication potential; MJ, mega joules; MRS, mineral resource scarcity potential; PMFP, fine particulate matter formation potential; PVC, polyvinyl chloride; ReTraCe, Realizing the Transition towards a Circular Economy; SDGs, Sustainable Development Goals; OIV, International Organization of Vine and Wine; TAP, terrestrial acidification potential; UNDP, United Nations Development Programme; WCP, water consumption potential.

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Circular Economy
Bioeconomy

residues and improving the overall environmental performance. By implementing the circular approach, environmental impacts in the global warming, freshwater eutrophication and mineral resource scarcity impact categories, in particular, resulted three times lower than in the linear system. The results achieved demonstrated that closing the loops in the wine industry, through the reuse of bio-based residues alternatively to fossil-based inputs within the production process, and integrating the traditional production system with new side production chains led to an upgrade of the wineries to biorefineries, towards more sustainable production patterns.

1. Introduction

In the last decades, production systems have operated within a 'take-make-use-dispose' paradigm, based on the extraction and often irresponsible use of finite natural resources (European Commission, 2020). In recent years, the concept of Circular Economy (CE) has emerged as a potential replacement of the current linear production model (Ellen Macarthur Foundation, 2015). Current global challenges like climate change, land, and ecosystem degradation, coupled with a growing demand for food, feed and energy, force us to seek new ways of producing and consuming as well as disposing residues and waste. Food waste is currently an important issue, both in developing and developed countries (FAO, 2018). Food waste is defined as end products of various food processing industries that have not been recycled or used for other purposes (Garcia-Gonzalez et al., 2015). These end products are discarded as waste since their economic value is lower than the cost of recovery (Ellen Macarthur Foundation, 2015). It is estimated that about 1.2 billion tons of foods are lost or wasted globally, representing approximately one-third of the edible parts of food produced for human consumption (FAO, 2011). The main challenge is transforming the waste into useful products that can be re-used in a circular perspective, also including the valorisation of the agricultural and food waste. This can be addressed by means of a sustainable and circular bioeconomy (European Commission, 2018a, b).

Italian wine industry can represent a suitable model for the application of the CE principles. According to the International Organization of Vine and Wine (OIV, 2019), Italy is the top leader country in wine production, closely followed by France and Spain, with 54.8 million hL produced in 2018, corresponding to 19% of global production worldwide. Italian wine is steadily exported to United States, Germany, and United Kingdom as key markets; sales, especially driven by exports, have pushed the total value for the wine sector to € 11 billion in 2018 (Zion Market Research, 2017). Furthermore, a constantly increasing trend towards the production of very high-quality wines is proven by the spreading of certification labels to 523 products (Cappellini, 2019). Alongside its leading position in exports and quality, the Italian wine sector also must deal with the enormous amount of waste or co-outputs it produces, the management of which is often cause of economic and environmental troubles. Indeed, the winery process generates different by-products, such as grape stalks, grape marc, exhausted yeasts, wine lees and highly loaded wastewaters, together with the wine product itself, achieving an overall volume of waste generated corresponding to around 20–30% of total mass of wine production (Zabaniotou et al., 2018). If not properly disposed of, winery wastes can be considered hazardous materials due to the high levels of organic content (Devesa-Rey et al., 2011). The efficient use of resources and the valorisation of such residues through appropriate recovery and recycling procedures is a noteworthy added value that perfectly fits the CE perspective, granting and consolidating the value of each element of the productive chain and deepening the awareness of action, essential to achieve a real change towards sustainability (Gullón et al., 2018; BIT, 2019).

The valorisation of residues is an innate feature of the winery industry: it suffices to consider that recycling of nutrients and carbon to agricultural soils is traditionally achieved by returning harvesting or processing residues to soils; studies have been carried out regarding the (vermi)composting of winery co-outputs to generate soil improver and the feeding of winery co-outputs to farm animals (Alba et al., 2019; Gómez-Brandón et al., 2019; Cortés et al., 2020). Furthermore, grape pomace has always been redistilled to produce spirits, such as the typical Italian "grappa". Nevertheless, changes in the EU policy have reduced the subsidies given to distilleries in an attempt to get more from this resource. Several value-added compounds from winery waste and by-products have great potential to be recovered and used in different applications. Therefore, the interest in developing products and processes for the valorisation of winery residues is increasingly gaining attention and this is evident from the number of scientific publications as well as of deposited patents (Mateo and Maicas, 2015; Aresta et al., 2015; Muhlack et al., 2018; Ferri et al., 2020; EPO, 2020). Recent advances in modern chemistry and biotechnology, academic awareness and industrial interest have permitted the study of these "wastes". New technologies are continuously being proposed not only for their re-use in agriculture, but also to produce common and novel products for other sectors, such as compost, animal feed and supplements, nutritional supplements, biofuel and fuel additives, besides other forms of bioenergy and platform chemicals. Global grape production could generate up to 5-13 Mt/yr of wasted biomass (Massey, 2015; Corbin et al., 2015). Fractions rich in sugars, such as grape pomace and lees, can be used to obtain grapeseed oil, tartaric acid and biodegradable polymers by enzymatic processes performed by bacteria. Other products like the trunk of the vine, stalk or grape skins are rich in cellulose fibres, which can be isolated and incorporated into conventional plastics (HaproWine, 2013) and more environmentally friendly plastic materials (Gontard et al., 2018). Grape pomace, if treated by hydrothermal carbonization at certain optimum conditions, can produce a mass yield of solid product char ranging between 47% and 78% of the original feedstock (Palaa et al., 2014). The chars produced with respect to their fuel properties, morphological and structural properties, and combustion characteristics, can be used as alternative energy sources (Palaa et al., 2014). Furthermore, the compositions of both red pomace/marc and white marc can be exploited with a view to using marc as raw material for biofuel production. According to Corbin et al. (2015), the theoretical amount of bioethanol that can be produced by fermentation of grape marc reaches 400 L/ton, leaving a polyphenol enriched fraction that may further be used in animal feed or as organic fertilizer. Red grape skins recovered from the pomace can be transformed into by-products with potential dietary anti-glycation agents, that can prevent the glycol-oxidative stress associated with type-2 diabetes. These by-products are useful as sources of cost-effective anti-glycation agents either as food ingredient or as a nutraceutical preparation (Harsha et al., 2013). Grape pomace can also be exploited to extract methanol/alcohol of good quality from the sweet pomace (Hang and Woodams, 2008; Ruberto et al., 2008). Zhang et al. (2017) compared two methods for the valorisation of grape pomace, which is the major component of wine production co-outputs, to add value to economic and environmental balance of the overall process. These processes involved combustion to produce electricity, and pyrolysis to produce biogas, bio-oil, and biochar. The detailed analysis of the wine lees fraction presents high concentrations of macronutrients and polyphenols and low concentrations of micronutrients and heavy metals (Devesa-Rey et al., 2011). Moreover, the presence of other compounds of potential interest such as polyphenols and antioxidants identify this stream as an ideal candidate to be valorised (Dimou and Koutelidakis, 2016; Martinez et al., 2016; Kopsahelis et al., 2018). Poveda et al. (2018) proposed revaluing the by-products of winemaking, grape pomace, wine lees and stems as a source of natural preservatives, whereas Nayak et al. (2018) developed a method for recovering polyphenols from exhausted grape pomace through activated carbon.

With the aim of a complete waste valorisation, the currently available research results on the use of winery waste provide a promising alternative to the current treatment techniques, that are focused on the waste remediation and treatment, rather than resource recovery, and confirm the importance of upgrading winery waste by indicating the possibility of obtaining quality co-products from waste that would have otherwise been thrown away in a linear system (Hang and Woodams, 2008). Nonetheless, some constraints are still unsolved. First of all, a shift from the lab scale to pilot studies is urgently required in order to assess the real feasibility of recovery processes (Cortés et al., 2019) and, secondly, the need for an environmental assessment of waste valorisation technologies on a case-by-case basis has been highlighted (Ripa et al., 2014; Fiorentino et al., 2017; Fiorentino et al., 2019). The challenge is to prove, together with the technical and economic feasibility, also the environmental advantages, in terms of lower impact over the entire production chain. For such circular initiatives, the risk for burden shift is concrete, in that benefits achieved in some impact categories may be countered by increased impacts in other categories. Moreover, the economic feasibility and efficiency depends on the seasonal availability of the waste, thus demanding judicious handling, treatment and planning (Gnansounou, 2017; Zacharofl, 2017).

An innovative approach consists in clustering the enterprises in a biorefinery perspective to obtain and recover a variety of useful co-products such as citric acid, grapeseed oil, tartaric acid and other platforms chemicals (Papadaki and Mantzouridou, 2019). A collective effort of all the involved stakeholders including researchers, farmers and consumers as well as policy makers is required to successfully use winery co-outputs as feedstock in the biorefinery concept (Gobert, 2019).

Presently, there is no scientific evidence regarding the environmental benefits of circular use of winery co-outputs as a resource (Zacharofl, 2017; Martins et al., 2018) and it has been highlighted that further research comparing linear product versions with their circular counterparts is strongly recommended (Harris et al., 2021). In spite of many previous studies concerning the valorisation of winery waste and the environmental assessment of wineries in a life cycle perspective (Petti et al., 2015; Iannone et al., 2016; Merli et al., 2017; Jourdaine et al., 2020), to the best of our knowledge, the design of a circular winery and its evaluation have not been reported so far. This study fills in the gap by performing a comprehensive Life Cycle Assessment (LCA) of a traditional wine production chain, highlighting the hotspots that present the highest environmental impacts. The novelty value of this study consists in the introduction of side production chains and of circular patterns within the linear production chain for valorising waste and minimizing the generated impacts, thus upgrading a traditional winery to a biorefinery concept. Moreover, a substantial number of LCAs of wine production has been carried out in the past, but according to Ferrara and De Feo (2018), site-specific LCAs are still scarce and the present study addresses this concern and deficiency. To this aim, site-specific data (referred to the year 2018) were provided from the wine company "I Borboni", producing Asprinio wine DOC (https://www.wine-searcher.com/regions-aversa+asprinio) in Campania Region (Italy), for the core processes (agricultural, vinification and bottling phases). These data were assessed in a life cycle perspective to quantify the environmental loads generated throughout the traditional production chain of wine. As a second step, based on literature data, two side production chains (grapeseed oil and tartrate production) were included and circular patterns were designed and introduced in the traditional production chain with the aim of valorising the winery residues and improving the overall environmental performance. The resulting environmental benefits were finally quantified by means of LCA. The match with value-adding side production chains and the savings from closed loops in the winery industry enhances the sustainability of the wine industry, thus providing an upgrade of the wineries to biorefineries, towards more sustainable production patterns.

2. Materials and methods

2.1. Case study

The object of this study is the Asprinio white wine, labelled with the Designation of Controlled Origin (DOC) since 1993, produced by a family-owned company called "I Borboni" located in Lusciano, near Aversa (Province of Caserta, Southern Italy). Asprinio is a strictly autochthonous grape variety and the production of this wine is characterized by the winemaking in underground tuff caves. The vineyard is 15 ha, with 50–80 plants/ha. The yield is on average 10 kg grapes/vine. In addition to the Asprinio variety, the company produces other grape varieties from the area: Coda di volpe IGP Beneventano, Falanghina IGP Campania, and Aglianico IGP Campania.

2.2. Method

The Life Cycle Assessment is a tool recommended by the European Union that evaluates and analyses the entire life cycle of a product, from its cradle to its grave. It is the methodological framework used in this paper as defined by ISO standards and ILCD Handbook guidelines (ISO 14040, 2006; ISO 14044, 2006; JRC, 2010). According to the ISO standards, the four phases (Goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment, Interpretation) are described in the following subsections.

2.2.1. Goal and scope definition

The goal of this study is the environmental evaluation of the wine production in a twofold perspective: (i) as a linear production (leading to the production of wine and by-products) and (ii) as a circular process based on the reuse of by-products, to produce not only wine but also other value-added products. The phases of the production processes were modelled according to the available primary data provided by "I Borboni". Academia and decision-makers can refer to this study to identify the hotspots influencing the environmental performance of winemaking and hence to plan strategies to achieve an optimized use of resources. The Functional Unit is a measure of the function of the system studied and provides a reference to which the inputs and outputs can be related (ISO 14040, 2006; ISO 14044, 2006). The Functional Unit (FU) chosen for this study, to which all input and output data are referred, is 1 bottle of wine, equivalent to 0.75 L. The timeframe is the year 2018. In this study, an attributional LCI modelling framework was applied and a cradle-to-gate approach was proposed, considering all stages, from the cultivation of the vine to the activities of the winery and the valorisation of the wine lees, prunings/stalks and grape pomace.

This study examines two main subsystems, namely the linear production chain (Subsystem 1) and the extended production biorefinery (Subsystem 2).

Subsystem 1 is the linear production chain which consists of three different phases:

(1) Agricultural phase. It starts in October and lasts till the end of January, involving the removal of the new vine shoots from the previous harvest, tying them upside down towards the soil, according to the type of cultivation of the vine, called Sylvot Upside Down. When the new vine shoots begin to sprout upwards from the end of April to the end of July, there is a vineyard treatment phase, which consists of the application of pesticides and fertilizers and soil cleaning, thanks to the use of specific agricultural machinery. Subsequently, between June and August,

summer pruning is carried out, through defoliation. Finally, from the end of August to the end of September, the grape harvest takes place, using plastic boxes that are subsequently transported to the wine making plant. The residues resulting from the pruning phases and the exhausted shoots are reused as soil improvers within the vineyard or can be used for energy recovery. From a traditional understanding of sustainability, the extended processes for bioenergy recovery from biomass would prevent the return of carbon and nitrogen as storages into the soil (Alba et al., 2019; Manso et al., 2016). However, since in this study the focus is on internal recycling to replace and substitute fossil derived fuels, the soil improvement option is disregarded, by opting for bioenergy recovery from the available stalks and prunings co-outputs.

(2) Wine production phase. It starts when the Asprinio grapes, produced at the vineyard, are delivered in plastic crates. Upon arrival, the grapes are crushed and destemmed, with the aim of completely removing the stalks. The removal of stalks is important because they release substances that affect the quality of wine. Although the stalks are traditionally reused as soil improvers in the vineyard, in this case, as in the Agricultural phase, the stalks are considered for bioenergy recovery through combustion. Subsequently, the de-stemmed grapes are transported to the pneumatic press for pressing, for the separation of the must from the pomace (a by-product) through the addition of potassium metabisulphite. The potassium metabisulphite acts as an antioxidant and antiseptic to protect the must from contact with oxygen. Before undergoing the fermentation process, the must is clarified through the floatation process, in order to remove visible suspended particles; in this case, the must is conveyed into a container in contact with a flotation machine which allows the separation of the solid part from the must, by introducing gaseous nitrogen at a certain pressure. In this phase, wine lees are obtained as by-products. Finally, the must is conveyed to the containers in the cave on the lower floor where the alcoholic fermentation takes place, initially activated by the inoculation of yeast and additives. During the fermentation, the yeasts transform the sugars present in the juice into ethanol and carbon dioxide. After the fermentation, the aging phase takes place and the wine is cleaned and separated from the rest of the lees and, finally, stabilized by an antioxidant, thus preserving the taste and color of wine. During the wine storage period in containers, numerous chemical-physical checks are carried out and tannins are usually added as antioxidants. Chemicals such as tartaric acid and bentonite are also added for stabilization in the latter stages, to avoid the formation of crystals and protein deposits in the wine bottle.

(3) Bottling phase. It involves the packaging of wine into glass bottles. As a first step, the Asprinio DOC wine is microfiltered to permanently eliminate impurities. Then, bottling, capping and labeling follow so that the wine is bottled in 0.75 L green glass bottles, using corks, PVC capsules (polyvinyl chloride) and paper labels. During bottling, potassium metabisulfite, metatartaric acid and tannin are added. Finally, the glass bottles are transferred into cardboard boxes of 6 bottles each.

Since the impacts of the three above phases were calculated and diagrammed independently from each other (for ease of comparison), the total impact of the linear winemaking needs these values to be added and this was performed later, in the final comparison of linear and circular systems.

As far as Subsystem 2 is concerned, in addition to the traditional production of wine, it also includes two side production chains, based on the employment of by-products of the linear production process (Subsystem 1) as feedstock for an extended production biorefinery. In particular, the use of grape pomace to make grapeseed oil and of wine lees to make calcium tartrate are investigated as examples of the valorization of by-products from the wine supply chain to reduce the impacts attributed to the production of wine. In the grapeseed oil production (side production chain 1), the oil content is traditionally extracted using physical pressing methods, which allow the recovery of an oil characterized by excellent quality with preserved components that are beneficial for health, even if the extraction yield is generally lower compared to the other conventional extraction methods which involve thermal or chemical treatment. Grapeseed oil is rich in phenolic compounds, fatty acids and vitamins, with economic importance to pharmaceutical, cosmetic, and food industry. Its use as an edible oil has also been suggested, especially due to its pleasant sensory characteristics (Garavaglia et al., 2016). In the case of the calcium tartrate production (side production chain 2), wine lees are collected and go through a solid-liquid separation process, which is then followed by an acidification process to remove the alcohol content from the wine lees. The dealcoholized wine lees undergo a chemical reaction which involves calcium carbonate and calcium chloride reagents, for the precipitation of potassium bitartrate which subsequently produces calcium tartrate crystals. The crystals are then concentrated and separated from the liquid fraction through centrifuges, hydro-cyclones and then dried separately. The produced calcium tartrate is stored in dedicated silos and then used to produce tartaric acid.

Besides the two investigated side production chains, in Subsystem 2 circular winery scenarios were also explored to highlight the different strategies for valuing winery waste, proposing the identification of critical points in the environmental profile of the grape pomace, prunings and wine lees before its implementation in a biorefinery system. In particular, three different scenarios were designed for sensitivity test purposes, assuming a substitution of the inputs, that resulted the main hotspots in the different investigated phases of the production patterns, with products recovered from the processing of winery co-outputs. The sensitivity of the LCA results to these changes was thus measured. A detailed description of the three proposed scenarios follows next:

Scenario 1: *Improved agricultural phase*. In this scenario, the diesel used in the agricultural phase is replaced by a biofuel, namely the fatty acid ethyl ester (FAEE). The grapeseed oil from the extended production biorefinery (Subsystem 2) can be sold to the market or, alternatively, be trans-esterified with the bioethanol obtained from the calcium tartrate production, to produce the biofuel-FAEE that has the potential to replace diesel. The inputs for the production of biofuel-FAEE were modelled based on the EcoInvent process “Vegetable oil methylester, esterification of soyabean oil”, substituting the soybean oil with grapeseed oil (Garavaglia et al., 2016). In particular, 1.72E−02 kg of grapeseed oil, referred to the FU of 1 bottle of wine, led to the production of 1.38E−02 kg of FAEE, considering a Higher Heating Value (HHV) for biodiesel between 39 and 43 MJ/kg *versus* 49.65 MJ/kg for diesel (Sivaramakrishnan, 2011; European Biofuels Technology Platform, 2011). Moreover, in this improvement scenario, an additional 50% reduction of fertilizers was accounted for, assuming a shift towards organic fertilizers/farming by using the exhausted pomace (1.63E−02 kg/FU).

Scenario 2: *Improved vinification phase.* In this circular scenario, a reduction in the electricity consumption can be achieved by replacing electricity with steam from prunings. The steam flow production process was modelled on the EcoInvent process for steam production from woodchips, taking into account a HHV of 18 MJ/kg for prunings (Manzone et al., 2016; Puglia et al., 2017). In particular, 1.429 kg of prunings and 1 L of water were required and a 300 kW capacity furnace was used. In the selected process inventory, only the biogenic CO_2 and CO emissions are included and the impacts of changes in soil carbon stocks as well as the N_2O

emissions from soil are excluded. An additional improvement was also proposed: yeast cells produced from the calcium tartrate production process were used to substitute the protein feed, crude fodder yeast in the wine making process.

Scenario 3: *Improved side production chain.* The extended production biorefinery also needs improvements and, from the preliminary analysis of the inventory data, the steam used in the distillation process was identified as a potential hotspot input flow in the process of producing calcium tartrate. In an improved scenario, this steam can be replaced by the bio-based steam that can be recovered from stalks and prunings and the process of recovering steam was modelled according to Scenario 2.

In this scenario the fate of prunings and stalks at the investigated site is for soil improvement purposes, to maintain the soil's nutrient stock. However, in the above considered scenarios referring to prunings and stalks, their handling fate is designed towards bioenergy recovery, to replace or substitute the identified hotspots generated from the use of fossil-derived electricity and steam. The development of such scenarios should, however, be cautiously applied, with the awareness and understanding that continuous combustion of the biomass (pruning residues and stalks) may in the long-term result in a decline in the soil's carbon and nitrogen stocks and eventually increase the global warming potential (Chiriacò et al., 2019).

For the sake of clarity, the investigated subsystems and scenarios (and the related activities) are schematically summarized in Table 1.

Based on Subsystems 1 and 2, and on the described scenarios, two final Circular Production systems (CP-A and CP-B) were analysed and compared to the linear production system (with and without allocation). In deeper detail, CP-A includes the combined environmental benefits and effects emanating from the suggested improvement scenarios (Scenarios 1 up to 3), involving the substitution of fossil-based inputs with co-products recovered from the extended production system. CP-B is similar to CP-A in many aspects, but differs in that grapeseed oil is sent to the market and considered for food purposes instead of producing the biofuel, in an effort to address the ongoing food *versus* biofuels debate.

The system boundaries of the investigated processes are shown in Fig. 1 and include all the material and energy input flows as well as emissions to soil, water and air. The treatment of wastewater and the processing of co-products to obtain value-added products are also accounted for.

A multi-output system, with two or more intermediate or final products, may require allocation, namely the partitioning of the input or output flows between the goods that are produced by the process under analysis (ISO 14044, 2006). Several allocation criteria can be adopted, according to the share of physical (mass, energy, exergy) flows associated to the products under examination, or according to the share of total economic value of the output, depending on the final goal of the assessment study. In this study, the economic allocation was avoided because it is too dependent on the country of production and because of the risk of price volatility (Goedkoop et al., 2016). Analogously, it was considered that mass allocation would not have fully estimated the value of the co-products (for example, 1 kg of oil does not have the same value as 1 kg of pomace). Although it is in principle possible to avoid allocation and assign all the environmental impacts to the main product (wine) and consider the by-products as waste to be discarded to landfills, an allocation based on exergy was performed as detailed below. The allocation, in percentage values, of the environmental load among the different product streams, according to their exergetic values, is shown in Table 2. The allocation by exergetic value considered the chemical exergy of each product as a proxy of its ability to do useful work. The chemical exergies (MJ/kg) of process products were calculated from the standard chemical exergies of pure substances and main mixture components (Szargut et al., 1988).

In order to evaluate the environmental benefits deriving from the processing of by-products to obtain energy and/or value added products in the extended production biorefinery (Subsystem 2), a system expansion (or avoided burden approach) was also performed. The system expansion allows to consider the avoided environmental costs deriving from the recovery of energy and materials: the impacts generated by the conventional production routes of primary materials that can be

Table 1
A summary of the investigated subsystems and scenarios and related activities.

Subsystem 1 (linear production chain) includes three production phases	
Production phase	Activities
Agricultural phase	Removal of the new vine shoots from the previous harvest
	Cultivation and vineyard treatment (fertilizer and chemical application)
	Grape harvest
Wine production phase	Crushing and destemming harvested grapes
	Separation of the must from the pomace by pressing
	Flotation, fermentation
	Wine storage
Bottling phase	Packaging of wine into glass bottles
Subsystem 2 (extended production biorefinery) includes two side production chains based on the utilization of the by-products from Subsystem 1	
Side production chain	Activities
1 — Grape seed oil production (from grape pomace)	Grape seed extraction and separation
	Oil extraction (physical pressing)
	Bottling
2 — Calcium tartrate production (from wine lees)	Solid liquid separation
	Acidification to remove the alcohol content from the wine lees
	Precipitation and crystallization
	Storage
Proposed circular winery scenarios for valuing winery waste	
Scenario 1 — Improved agricultural phase	Substituting diesel used in the agricultural phase with a biofuel obtained by transesterification of grapeseed oil
	50% reduction of fertilizers
Scenario 2 — Improved vinification phase	Replacing grid-electricity with steam obtained from prunings
	Substituting protein feed, crude fodder yeast with yeast cells obtained from Subsystem 2
Scenario 3 — Improved calcium tartrate production	Replacing industrial steam with bio-based steam recovered from stalks and prunings

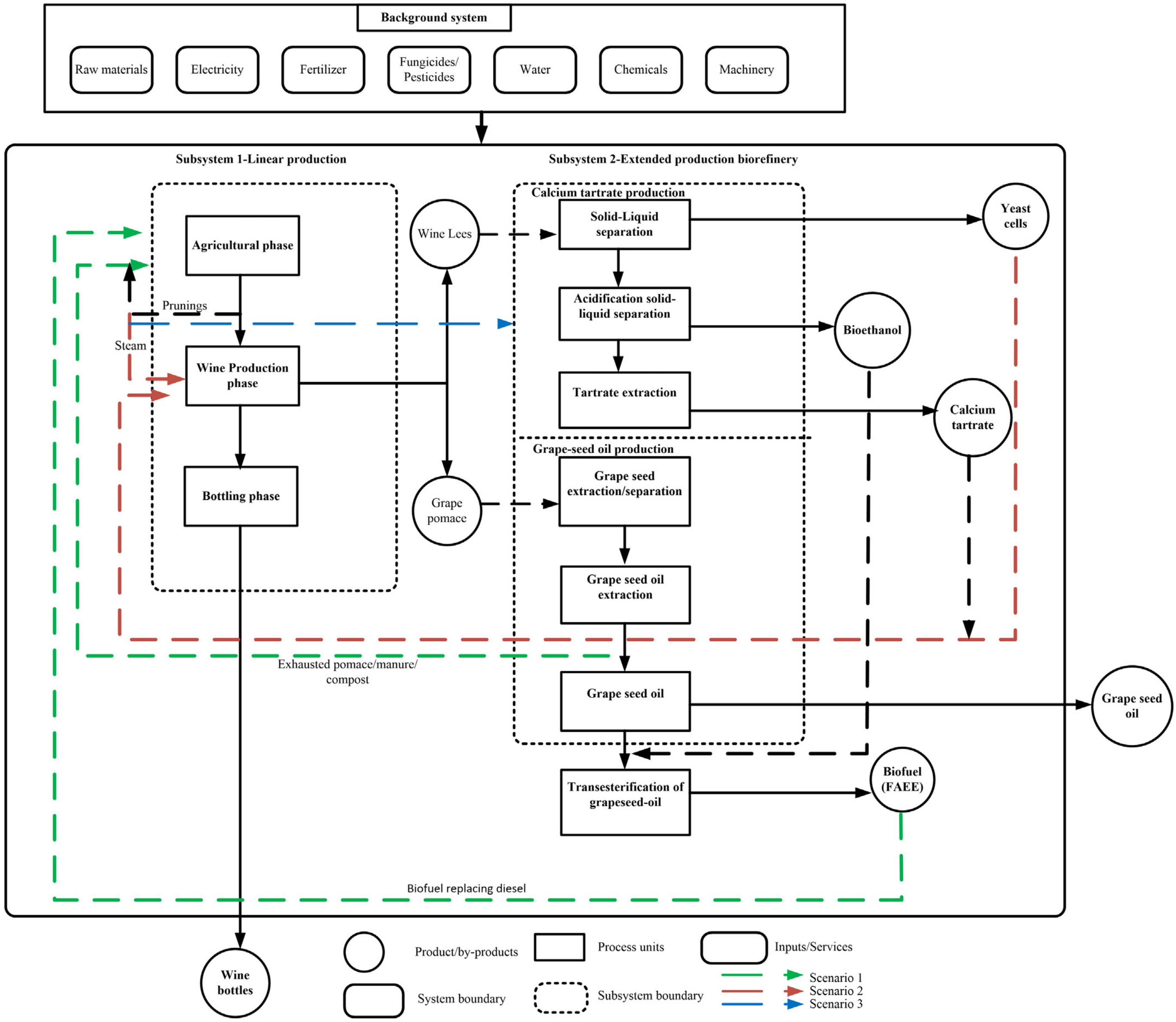


Fig. 1. Process flow chart and investigated system boundary.

Table 2
Percentages of exergetic allocation (Further details are provided in Appendix 1 – Table A1).

Product and co-products	% allocation
Subsystem 1	
Wine	69.20
Stalks	16.51
Wine lees	0.29
Grape pomace	14.00
Subsystem 2	
Grapeseed oil	85.46
Exhausted flour	14.54
Side production chain 2	
Bioethanol	2.11
Calcium tartrate	1.99
Yeast cells	95.90

substituted by the secondary recovered goods are avoided and can be subtracted from the accounting of the system impacts. In this study, in particular, since tartaric acid can be used as preservative in the food industry and can replace another preservative such as citric acid, the impacts related to the conventional production of citric acid (according to the EcoInvent v.3.5 database) can be subtracted by the impacts of the system in which tartaric acid is produced and assumed to be used alternatively to citric acid. Analogously, the impacts of the production of soybean oil can be avoided if the grapeseed oil, produced in the investigated system, is assumed to be used for food purposes. It was assumed that grapeseed oil can replace soybean oil on the basis of their chemical properties and functional similarities, as they have a very similar fatty acids profile (Nierenberg, 2017). Similarly, the assumption to use esterified grapeseed oil or biofuel for energy purposes allows to subtract the impacts related to a corresponding amount of ethanol or diesel, respectively, from the account of the total impacts.

2.2.2. Life cycle inventory

The life cycle inventory is the compilation of the data set for evaluation and involves the collection of quantitative input/output data flows

Table 3
List of products and co-products for each phase of the investigated systems, referred to the selected FU (1 bottle of wine).

Main product	Amount	Co-products	Amount
Subsystem 1			
Agricultural phase			
Grapes	1.08E0 kg	Prunings	4.50E−1 kg
Wine production phase			
Wine	7.42E−1 kg	Grape pomace	1.40E−1 kg
		Wine lees	9.31E−4 kg
		Stalks	6.40E−2 kg
Bottling phase			
Bottles	1 item		
Subsystem 2			
Side production chain 1			
Grapeseed oil	1.72E−2 kg	Exhausted flour	1.60E−2 kg
Side production chain 2			
Calcium tartrate	5.45E−5 kg	Bioethanol	2.62E−5 kg
		Yeast cells	2.24E−4 kg

for the system (Cortés et al., 2019). The inventory of this study is provided in Appendix 2 (Table A2), with reference to the selected FU (1 bottle of wine).

For the sake of clarity, Table 3 below lists the amounts of the main products and co-products that are obtained in each phase of the investigated subsystems.

Input and output data for the foreground of Subsystem 1 are primary data, provided by the company under study. As far as the Subsystem 2 is concerned, data sources were multiple. Olitalia company, located 540 km away from the wine production site, provided primary data concerning the production of grapeseed oil from grape pomace. Furthermore, data regarding the valorisation of the by-products of wine production (wine lees and grape pomace) came from complementary sources including scientific literature and EcoInvent v.3.5 database. The process related to the production of calcium tartrate was modelled on the inventory of a previous study by Cortés et al. (2019). Primary data were collected by means of personal interviews, whereas background data were derived from the most updated version of EcoInvent database, such as averaged European data for materials and chemicals and the medium-voltage Italian electricity mix. Transport was included in Subsystem 1, according to the primary data provided for the transport from the vineyard to the winemaking plant. On the other hand, no additional transport was accounted for in Subsystem 2, assuming that all the feedstocks were by-products of Subsystem 1 and were processed in the same company. The avoided environmental loads from the production of energy by means of conventional routes were included, crediting Italian average mix for heat and electricity production on the base of the calorific value of prunings and stalks (Manzone et al., 2016; Puglia et al., 2017). The production of diesel was assumed to be avoided thanks to the production of biofuel, with a substitution ratio of 1:1.09 kg (European Biofuels Technology Platform, 2011).

2.2.3. Life cycle impact assessment

The software SimaPro 9.0.0.49 (Goedkoop et al., 2016; Oele, 2019), coupled with the database EcoInvent v.3.5, was used to analyse the Life Cycle Inventory (Ecoinvent, 2020; Wernet et al., 2016). Within the database, allocation at point of substitution, unit process datasets were chosen. The ReCiPe 2016 Midpoint (H) methodology was selected for the characterization and normalization of the impact categories (Vezzoli, 2018; PRé, 2016). This method provides a common framework in which mid-point impact categories can be investigated (Goedkoop et al., 2009). In this study, the impact categories reported in Table 4 were analysed, in accordance with other scientific studies (Meneses et al., 2016; Cortés et al., 2019), in order to support decision making by means of a simplified overall assessment across the supply chain from linear processes to circular ones.

Finally, the uncertainty of the LCA results, related to the uncertainty of parameters in unit process data and characterization factors as well as of model choices, was calculated through the Monte Carlo analysis, in order to estimate a confidence interval for the results of the final product system (Bamber et al., 2020).

3. Results

This section shows the results of the environmental assessment of the linear production of wine (Subsystem 1), of the extended production biorefinery (Subsystem 2), and finally the environmental benefits emanating from the suggested improvement scenarios in both the subsystems, if co-products are utilized to substitute input flows or in alternative supply chains.

3.1. Linear production of wine (Subsystem 1)

The environmental impacts associated with the linear production of wine (Subsystem 1), including Agricultural phase, Wine production and Bottling phases, are thoroughly analysed. Fig. 2 shows the normalized impacts of the linear production. All impacts relate to the functional unit of 1 bottle of Asprinio wine (0.75 L).

By observing the normalized data (dimensionless impact distribution values) in Fig. 2, the phase with the highest environmental load is the bottling phase (63% on average), according to the results obtained by Meneses et al. (2016). In deeper detail, the glass production was identified as the major contributor to the environmental load of the entire wine production process for the studied system. The agricultural phase contributes to the overall impact load at an extent of 14.3% on average, mainly due to the heavy reliance on pesticide application, tillage and fertilization. The wine production (or vinification) phase gives a relative contribution of 22.7%, largely due to the use of electricity to run the machinery involved in the wine making process. The categories in which the investigated linear system is mostly impacted are HTP_c (9.22E−03), FEP (3.89E−04), FRS (2.64E−04) and, to a lesser extent, TAP (3.82E−05) and GWP (3.47E−05). A thorough analysis of each examined phase follows, with the aim of identifying the main hotspots calling for an improvement.

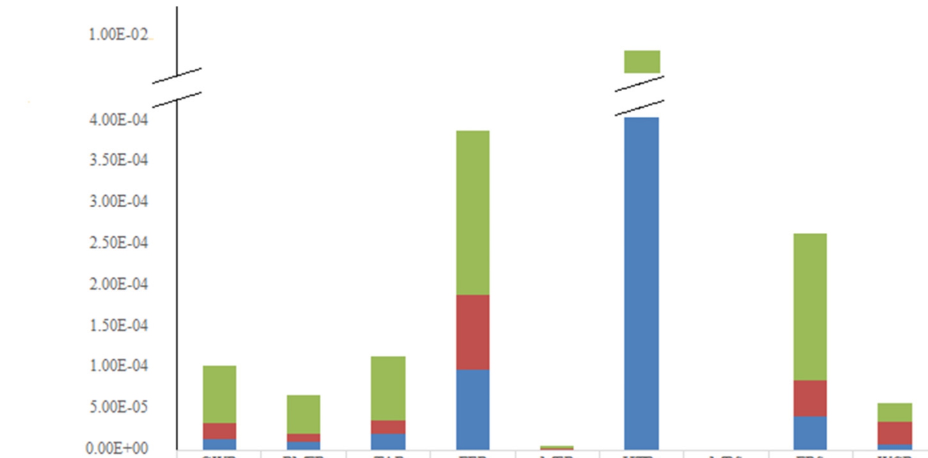
3.1.1. Agricultural phase

Fig. 3 shows the characterized impacts of the agricultural phase referred to the selected FU, after allocation to by-products is performed.

In the case of the agricultural phase, the HTP_c impact category results mostly affected by copper oxide containing compounds (65%), mancozeb fungicide (6%), diesel consumption (7.8%) and production of plastic laces used for winter pruning (8%). In the FEP category, the greatest contribution derives from the use of pesticides (44%), fertilizers (16.6%) and mancozeb (19%). It is worth noting that the main impact is given by copper-based pesticides, used as fungicides against mycoses and bacteriosis that can attack the vine. For the FRS impact category, the input with the highest environmental load is represented by the diesel (73%), used in all the operations carried out in the agricultural phase,

Table 4
Impact categories considered within the ReCiPe 2016 Midpoint (H) v.1.03 impact method.

Impact category	Unit	Abbreviation
Global warming potential	kg CO_2 eq	GWP
Fine particulate matter formation potential	kg PM2.5 eq	PMFP
Terrestrial acidification potential	kg SO_2 eq	TAP
Freshwater eutrophication potential	kg P eq	FEP
Marine eutrophication potential	kg N eq	MEP
Human carcinogenic toxicity potential	kg 1,4-DCB	HTP_c
Mineral resource scarcity potential	kg Cu eq	MRS
Fossil resource scarcity potential	kg oil eq	FRS
Water consumption potential	m^3	WCP



	GWP	PMFP	TAP	FEP	MEP	HTPc	MRS	FRS	WCP
Bottling phase	7.01E-05	4.74E-05	7.72E-05	1.99E-04	3.67E-06	5.83E-03	1.25E-08	1.78E-04	2.24E-05
Wine production phase	1.88E-05	9.59E-06	1.67E-05	9.04E-05	1.25E-06	2.11E-03	4.46E-09	4.45E-05	2.71E-05
Agricultural phase	1.53E-05	1.08E-05	2.06E-05	9.95E-05	1.59E-06	1.27E-03	8.98E-09	4.16E-05	8.57E-06

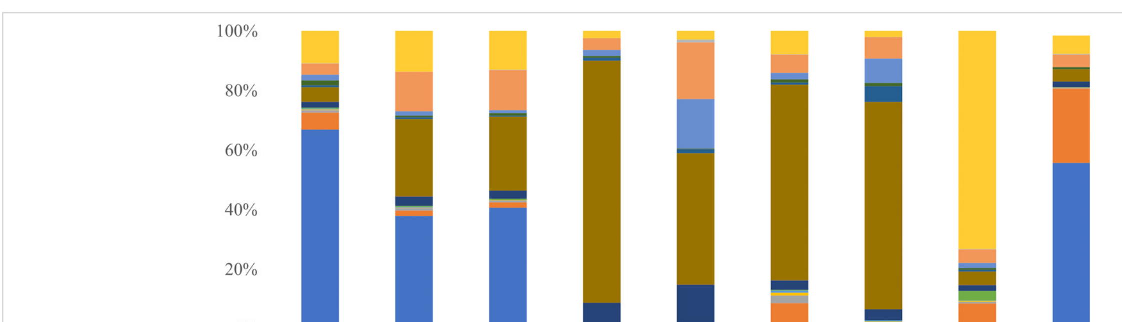
Fig. 2. Normalized impacts distribution of the linear production of wine, referred to a functional unit of 1 bottle of Asprinio wine. Note: The contribution of Wine production phase and Bottling phase cannot be clearly shown in the column HTP_c for graphical reasons, but its value is reported in the table below the diagram.

such as the treatments of the vineyard or the collection and transport of the grapes. The use of diesel also releases local emissions which contribute to GWP at an extent of 10.8%.

3.1.2. Wine production phase

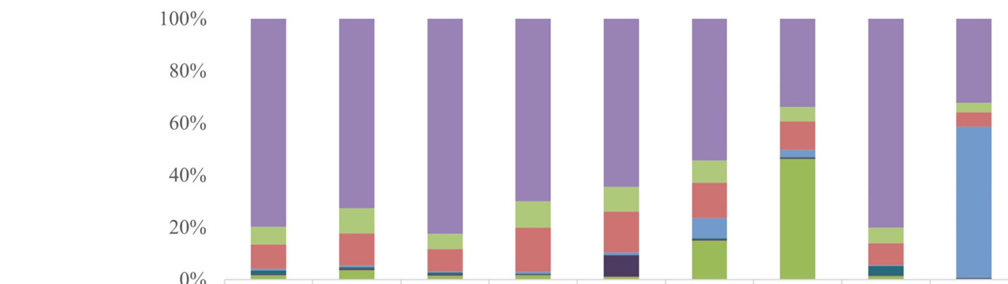
Fig. 4 shows the characterized impacts related to the wine production (vinification) phase. The calculation is performed to quantify the actual impacts of the vinification process, with reference to one bottle as functional unit. The impacts related to the production of grapes (associated to the grapes produced) are not included in the analysis of this phase, in order to account only for the actual impacts generated by the wine production phase.

The major contribution to the HTP_c category comes from the electricity consumption (54.4%). Similarly, for the Fossil resource scarcity, GWP and FEP categories, electricity consumption results the main hotspot with a share of 80.1%, 79.7% and 70%, respectively. In the vinification phase, large volumes of water are also consumed and, as expected, this influences the water consumption category, at an extent of 58%, with a contribution of 32.2% also given by the electricity used for the production and supply of tap water. The fish residue, reported among the inputs, has an insignificant environmental load and refers



	kg CO2 eq GWP	kg PM2.5 eq PMFP	kg SO2 eq TAP	kg P eq FEP	kg N eq MEP	kg 1,4-DCB HTPc	kg Cu eq MRS	kg oil eq FRS	m3 WCP
Diesel	1.32E-02	3.79E-05	1.10E-04	1.55E-06	2.06E-07	2.77E-04	2.19E-05	2.99E-02	1.46E-04
Non-ionic surfactant	9.29E-05	1.31E-07	3.02E-07	2.47E-08	7.09E-08	2.82E-06	2.24E-07	3.03E-05	4.02E-06
Mancozeb	4.67E-03	3.67E-05	1.14E-04	2.56E-06	1.39E-06	2.15E-04	7.76E-05	1.89E-03	1.01E-04
Cyclic N-compound	2.22E-03	3.87E-06	8.26E-06	1.29E-06	1.22E-06	7.60E-05	8.83E-05	6.68E-04	-2.70E-05
Calcium nitrate	2.12E-03	1.97E-06	7.02E-06	3.66E-07	2.00E-08	3.97E-05	1.09E-05	2.47E-04	1.64E-05
[thio]carbamate-compound	7.19E-04	1.42E-06	3.16E-06	6.76E-07	9.47E-08	2.63E-05	5.73E-05	2.50E-04	-8.52E-06
Copper oxide	5.85E-03	7.20E-05	2.10E-04	5.25E-05	3.22E-06	2.31E-03	7.51E-04	1.80E-03	9.44E-05
Phenoxy-compound	2.73E-05	4.90E-08	9.43E-08	1.16E-08	1.05E-09	1.05E-06	7.61E-08	9.96E-06	6.54E-07
Pyrethroid-compound	8.75E-05	1.36E-07	3.07E-07	2.82E-08	6.18E-09	3.12E-06	1.90E-07	2.99E-05	-1.21E-06
Organophosphorus-compound	2.38E-03	8.69E-06	2.30E-05	4.48E-06	9.11E-07	1.11E-04	3.92E-05	7.94E-04	4.55E-05
Sulfur	5.10E-04	1.20E-06	3.58E-06	4.71E-08	7.30E-09	8.11E-06	6.54E-07	1.36E-03	2.90E-06
Agricultural trailer	2.22E-04	4.38E-07	8.67E-07	9.65E-08	6.90E-09	2.72E-05	3.65E-06	4.97E-05	1.59E-06
Agricultural machinery	3.08E-04	5.95E-07	1.07E-06	1.47E-07	8.96E-09	3.60E-05	7.18E-06	6.54E-05	1.78E-06
Tractor	9.89E-04	2.05E-06	4.30E-06	6.15E-07	4.18E-08	8.84E-05	1.65E-05	2.78E-04	6.68E-06
Polyvinylchloride	6.93E-03	5.26E-06	1.56E-05	2.52E-07	1.05E-07	3.03E-04	3.59E-06	3.46E-03	5.87E-04
Local emissions	8.17E-02	1.05E-04	3.44E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.32E-03

Fig. 3. Characterized impacts of the agricultural phase, referred to a functional unit of 1 bottle of Asprinio wine.



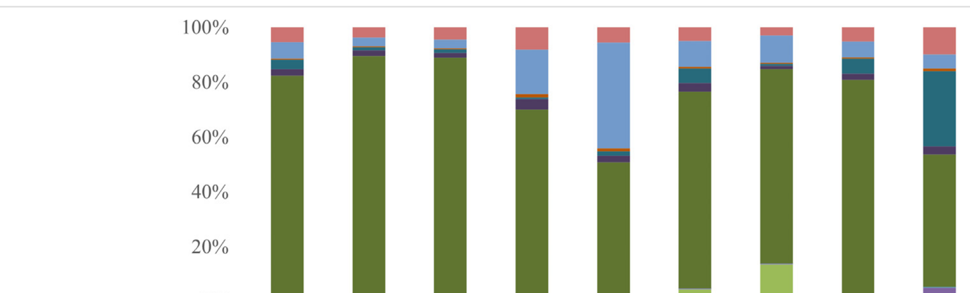
	kg CO2 eq GWP	kg PM2.5 eq PMFP	kg SO2 eq TAP	kg P eq FEP	kg N eq MEP	kg 1,4-DCB HTPc	kg Cu eq MRS	kg oil eq FRS	m3 WCP
Electricity	1.20E-01	1.78E-04	5.65E-04	4.11E-05	3.70E-06	3.18E-03	1.81E-04	3.50E-02	2.33E-03
Sodium hydroxide	1.02E-02	2.36E-05	3.96E-05	5.93E-06	5.47E-07	4.95E-04	2.95E-05	2.59E-03	2.59E-04
Sodium hypochlorite	1.42E-02	3.04E-05	5.86E-05	9.95E-06	8.97E-07	7.98E-04	5.84E-05	3.66E-03	3.96E-04
Tap water	7.98E-04	1.41E-06	3.04E-06	4.58E-07	5.17E-08	4.48E-04	1.50E-05	1.83E-04	4.19E-03
Lithium chloride	2.58E-07	5.29E-10	1.23E-09	1.87E-10	9.43E-11	2.42E-08	8.10E-08	6.08E-08	4.74E-09
Polypropylene	2.14E-03	1.73E-06	5.25E-06	7.33E-08	1.05E-08	3.79E-05	4.16E-07	1.54E-03	1.55E-05
Protein feed	4.61E-04	5.67E-07	2.04E-06	7.78E-08	4.65E-07	7.93E-06	7.99E-07	5.31E-05	7.73E-06
Benzoic acid	2.66E-05	2.36E-08	6.46E-08	6.55E-09	4.65E-10	6.68E-07	4.13E-08	1.75E-05	4.37E-07
Potassium sulfate	7.92E-05	2.46E-07	7.00E-07	4.74E-08	6.01E-09	4.42E-06	6.90E-07	2.60E-05	1.92E-06
Bentonite	7.52E-06	1.63E-08	3.93E-08	1.64E-09	1.26E-10	2.65E-07	1.71E-06	2.27E-06	7.05E-08
Chemical, organic	6.62E-05	8.69E-08	1.97E-07	1.39E-08	1.06E-09	1.68E-06	9.74E-08	4.38E-05	1.34E-06
Fish residues	1.30E-06	1.87E-09	4.27E-09	1.09E-10	1.11E-11	2.88E-08	2.72E-09	4.58E-07	4.06E-09
Nitrogen, liquid	1.20E-04	1.98E-07	5.20E-07	1.25E-07	9.01E-09	7.31E-06	1.85E-07	3.17E-05	5.99E-06
Steel, chromium steel	2.35E-03	8.75E-06	9.99E-06	9.15E-07	5.37E-08	8.63E-04	2.47E-04	5.30E-04	1.12E-05

Fig. 4. Characterized impacts of the wine production phase, referred to a functional unit of 1 bottle of Asprinio wine.

to the animal protein that works as a filter, binding dead yeast cells, bits of grape, stems, and other possible by-products that can be then removed from the liquid.

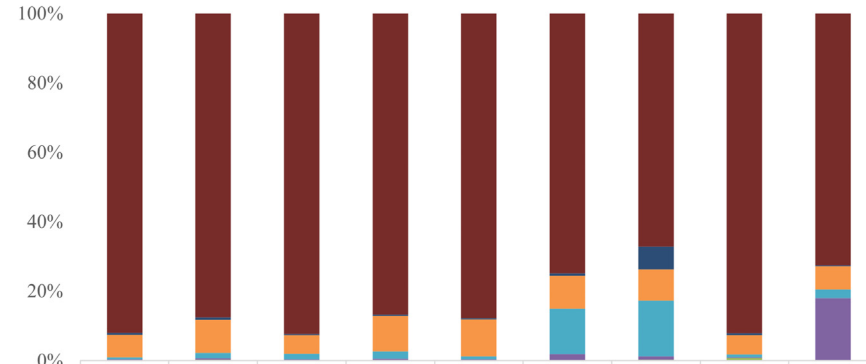
3.1.3. Bottling phase

Fig. 5 shows the characterized impacts of the bottling phase. Impacts from previous grapes and wine production steps were not included in



	kg CO2 eq GWP	kg PM2.5 eq PMFP	kg SO2 eq TAP	kg P eq FEP	kg N eq MEP	kg 1,4-DCB HTPc	kg Cu eq MRS	kg oil eq FRS	m3 WCP
Electricity	3.03E-02	4.50E-05	1.42E-04	1.04E-05	9.33E-07	8.03E-04	4.57E-05	8.81E-03	5.88E-04
Linerboard	3.33E-02	3.80E-05	9.69E-05	2.10E-05	6.53E-06	1.51E-03	1.46E-04	1.02E-02	3.05E-04
Paper, woodcontaining	2.47E-03	4.07E-06	1.10E-05	1.63E-06	1.60E-07	1.11E-04	7.07E-06	7.59E-04	5.65E-05
Polyvinylchloride	1.93E-02	1.47E-05	4.34E-05	7.02E-07	2.91E-07	8.46E-04	1.00E-05	9.65E-03	1.64E-03
Cork slab	1.28E-02	2.56E-05	5.79E-05	5.06E-06	4.00E-07	5.22E-04	1.92E-05	3.77E-03	1.86E-04
Packaging glass	4.59E-01	1.08E-03	2.80E-03	8.94E-05	8.51E-06	1.16E-02	1.06E-03	1.40E-01	2.88E-03
Polypropylene, granulate	5.80E-05	4.70E-08	1.42E-07	1.99E-09	2.86E-10	1.03E-06	1.13E-08	4.16E-05	4.20E-07
Benzoic acid	3.85E-05	3.42E-08	9.35E-08	9.48E-09	6.73E-10	9.66E-07	5.97E-08	2.53E-05	6.32E-07
Potassium sulfate	5.73E-05	1.78E-07	5.06E-07	3.43E-08	4.35E-09	3.19E-06	4.99E-07	1.88E-05	1.39E-06
Acetoacetic acid	9.47E-04	1.16E-06	2.67E-06	2.90E-07	1.56E-08	2.41E-05	2.23E-06	3.64E-04	1.29E-05
Tap water	5.64E-05	9.98E-08	2.15E-07	3.24E-08	3.65E-09	3.16E-05	1.06E-06	1.29E-05	2.96E-04
Steel, chromium steel	1.95E-03	7.24E-06	8.26E-06	7.57E-07	4.44E-08	7.14E-04	2.04E-04	4.39E-04	9.22E-06

Fig. 5. Characterized impacts of the bottling phase, referred to a functional unit of 1 bottle of Asprinio wine.



	kg CO2 eq GWP	kg PM2.5 eq PMFP	kg SO2 eq TAP	kg P eq FEP	kg N eq MEP	kg 1,4-DCB HTPc	kg Cu eq MRS	kg oil eq FRS	m3 WCP
Electricity	8.64E-03	1.28E-05	4.06E-05	2.96E-06	2.66E-07	2.29E-04	1.31E-05	2.52E-03	1.68E-04
Clay plaster	4.91E-05	8.84E-08	1.90E-07	1.19E-08	7.97E-10	1.81E-06	1.27E-06	1.49E-05	5.86E-07
Sodium hydroxide	6.07E-04	1.39E-06	2.35E-06	3.51E-07	3.24E-08	2.93E-05	1.75E-06	1.53E-04	1.54E-05
Phosphoric acid	5.48E-05	2.45E-07	6.77E-07	7.30E-08	2.34E-09	3.99E-05	3.14E-06	2.29E-05	5.91E-06
Tap water	2.36E-05	5.03E-08	8.67E-08	1.24E-08	9.41E-10	5.18E-06	1.67E-07	5.82E-06	4.13E-05
Hexane	1.36E-05	3.28E-08	9.10E-08	3.61E-09	2.83E-10	4.49E-07	5.31E-08	1.94E-05	2.53E-07

Fig. 6. Characterized impacts for grapeseed oil production from grape pomace, referred to the amount of co-product (seed oil) associated to a functional unit of 1 bottle of Asprinio wine.

the assessment of this phase, to allow for comparison of the costs and impacts of the different phases individually.

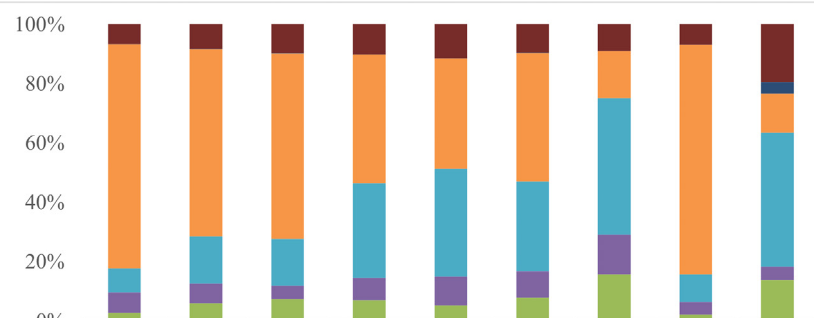
In the bottling phase, the greatest impacts generated are caused by the production of packaging glass and amount to 71.7% in HTP_c, 80.4% in FRS and 81.9% in GWP. The employment of lineboard material (10%), electricity (5%) and polyvinylchloride as bulk polymerized plastic (5%) contributes to a lesser extent.

3.2. Extended production biorefinery (Subsystem 2)

In order to further decrease the unit costs and impacts of the co-products from the linear production of wine, these co-products can be considered as feedstock to extract chemicals or produce secondary generation co-products, such as grapeseed oil and calcium tartrate. Following this logic, costs and impacts can be shared among the output flows from the linear production system. In this section, the processes considered in Subsystem 2 (grapeseed oil production and calcium tartrate production) are analysed as separated steps to highlight the main hotspots calling for an improvement.

3.2.1. Side production chain 1: grapeseed oil production

Fig. 6 shows the characterized impacts related to the grapeseed oil production. The process of extracting grapeseed oil is mainly a physical process and it requires electricity to mechanically run the oil-extracting machine. Therefore, electricity results a relevant hotspot, contributing between 67% and 92% in all the impact categories. Chemicals, such as sodium hydroxide and phosphoric acid are also used, generating overall impacts that range from 6.4% in the FRS impact category to 25.2% in



	kg CO2 eq GWP	kg PM2.5 eq PMFP	kg SO2 eq TAP	kg P eq FEP	kg N eq MEP	kg 1,4-DCB HTPc	kg Cu eq MRS	kg oil eq FRS	m3 WCP
Electricity	1.09E-06	1.62E-09	5.15E-09	3.74E-10	3.37E-11	2.90E-08	1.65E-09	3.19E-07	2.13E-08
Tap water	8.39E-10	1.49E-12	3.20E-12	4.82E-13	5.44E-14	4.71E-10	1.58E-11	1.93E-10	4.40E-09
Heat	1.23E-05	1.23E-08	3.29E-08	1.60E-09	1.09E-10	1.31E-07	2.90E-09	3.60E-06	1.43E-08
Hydrochloric acid	1.33E-06	3.09E-09	8.21E-09	1.17E-09	1.07E-10	9.19E-08	8.49E-09	4.27E-07	4.94E-08
Calcium carbonate	1.11E-06	1.29E-09	2.45E-09	2.78E-10	2.87E-11	2.71E-08	2.48E-09	2.01E-07	4.91E-09
Calcium chloride	4.51E-07	1.17E-09	3.85E-09	2.57E-10	1.53E-11	2.36E-08	2.90E-09	9.89E-08	1.52E-08

Fig. 7. Characterized impacts of calcium tartrate production, referred to a functional unit of 1 bottle of Asprinio wine.

Table 5
Characterized impacts of each improvement scenario *versus* the corresponding Business As Usual (BAU) scenario, referred to a functional unit of 1 bottle of Asprinio wine.

Impact category	Unit	Agricultural phase		Wine production phase		Extended production-calcium tartrate	
		BAU	Scenario 1	BAU	Scenario 2	BAU	Scenario 3
GWP	kg CO_2 eq	1.22E−01	1.21E−01 (−0.8%)	2.19E−01	7.65E−02 (−65.1%)	1.63E−05	2.89E−06 (−82.3%)
PMFP	kg $PM_{2.5}$ eq	2.77E−04	2.79E−04 (+0.7%)	3.57E−04	1.67E−04 (−53.2%)	1.95E−08	5.55E−09 (−71.5%)
TAP	kg SO_2 eq	8.45E−04	8.48E−04 (+0.4%)	9.97E−04	3.85E−04 (−61.4%)	5.25E−08	1.45E−08 (−72.4%)
FEP	kg P eq	6.46E−05	6.77E−05 (+4.6%)	8.54E−05	4.21E−05 (−50.7%)	3.67E−09	1.70E−09 (−53.7%)
MEP	kg N eq	7.32E−06	7.50E−06 (+2.4%)	8.36E−06	4.68E−06 (−44.0%)	2.94E−10	1.51E−10 (−48.6%)
HTP_c	kg 1,4-DCB	3.52E−03	3.64E−03 (+3.3%)	8.51E−03	4.98E−03 (−41.5%)	3.03E−07	1.43E−07 (−52.8%)
MRS	kg Cu eq	1.08E−03	1.12E−03 (+3.6%)	7.79E−04	7.77E−04 (−0.3%)	1.84E−08	1.38E−08 (−25.0%)
FRS	kg oil eq	4.08E−02	3.88E−02 (−4.9%)	6.35E−02	2.31E−02 (−63.6%)	4.64E−06	7.26E−07 (−84.4%)
WCP	m^3	2.29E−03	2.28E−03 (−0.4%)	1.05E−02	7.79E−03 (−25.8%)	1.09E−07	7.39E−08 (−32.2%)

MRS impact category. The impacts related to the production of grape pomace are not shown here, in order to focus on the impacts coming from the input and output flows involved in the processing steps of the investigated side production chain.

3.2.2. Side production chain 2: calcium tartrate production

Fig. 7 shows the characterized impacts related to the calcium tartrate production from wine lees. As already shown for the grape pomace in the grapeseed oil production, wine lees are co-products of the wine production process and their contribution to the total impacts is not shown here, to pinpoint the hotspots of the production process itself. The key input threatening the sustainability of this side production chain is represented by the heat generated from steam, with contributions of 75% in GWP and 77% in FRS impact categories. Steam consumption is very high, as it is used in the distillation process to evaporate water from the antioxidant-rich stream. This consumption, together with the fact that obtaining steam is an activity with high energy requirements (Nieuwlaar et al., 2015), explains the load of the environmental impact derived from the use of steam. The production of hydrochloric acid and calcium chloride as ingredients in this process, also represents a hotspot. In particular, hydrochloric acid directly contributes to negative impact on SOP (46%), FEP (31%), HTP_c (30%) and MEP (28%). Impacts deriving from electricity are around 14%, on average. Much of the electricity consumption (1.2E−04 kWh/FU) corresponds to the operation of disc centrifuges, which are used to separate value-added products from the solution (Cortés et al., 2019).

3.3. Combined benefits derived from circular winery scenarios

In this section, circular scenarios to further close the loop and ensure sustainability of both the linear and extended biorefinery production processes are proposed and combined. The benefits of combining the proposed scenarios with an enhanced circularity degree are expressed in the overall environmental load associated with the production of a bottle of wine. When fossil-based inputs (diesel, electricity, steam and chemicals) used in the production chain are substituted by means of bio-based counterparts recovered from the production chain by-products (biofuel, bioenergy, yeast cells, grapeseed oil, calcium tartrate), the environmental burden of the production of wine is expected to change. To this aim, the circular scenarios are explored within a system expansion approach, as described in Section 2.2.1, and evaluated against the linear production system (Subsystem 1) to highlight the overall benefits of circularity.

In Table 5, the impacts generated from the suggested scenarios, aimed at enhancing the agricultural phase, the wine production phase and the side production chain of calcium tartrate, are compared to the impacts of the Business As Usual (BAU) scenarios of the corresponding phase, in which there is no substitution of input flows. The differences of the generated impacts are also reported as percentage values (negative values indicate a reduction of the impacts in the improved scenario *versus* the BAU scenario, while positive values indicate an increase of the impacts). These differences in the generated impacts represent a measure of the sensitivity of the LCA results to the proposed changes of the input flows.

The benefits of substituting fossil-based input flows with the bio-based counterparts obtained from the extended production biorefinery system can be observed. In the Agricultural phase (Scenario 1), the substitution of fossil diesel with a biofuel derived from the grapeseed oil together with the reduction of fertilizers application by 50% generate a slight environmental load decrease in the GWP, FRS and WCP impact categories. The minor increases in the remaining impact categories can be attributed to the environmental burden generated by the grape pomace treatment in the extended production process. In the wine production phase (Scenario 2) and in the extended production system (Scenario 3), the substitution of the fossil-based electricity and steam with the bioenergy recovered from the valorisation of prunings and stalks produces significant decreases in all the investigated impact categories.

4. Discussion

4.1. Linear production system versus circular production systems

In order to have an overall outlook on the environmental implications and benefits of linear *versus* circular production systems, a comparison among different systems, based on the above mentioned

Table 6
Characterized impacts of linear and circular production systems, referred to a functional unit of 1 bottle of Asprinio wine.

Impact category	Unit	Linear − without allocation	Linear − with allocation	CP-A	CP-B
GWP	kg CO_2 eq	1.88E+00	1.13E+00	6.80E−01	5.68E−01
PMFP	kg PM2.5 eq	4.10E−03	2.48E−03	1.59E−03	1.48E−03
TAP	kg SO_2 eq	1.19E−02	6.97E−03	4.26E−03	4.13E−03
FEP	kg P eq	7.93E−04	4.14E−04	2.33E−04	2.19E−04
MEP	kg N eq	8.70E−05	4.43E−05	2.87E−05	−4.40E−05
HTP_c	kg 1,4-DCB	5.63E−02	3.37E−02	2.38E−02	2.27E−02
MRS	kg Cu eq	1.22E−02	6.13E−03	3.37E−03	3.24E−03
FRS	kg oil eq	6.05E−01	3.61E−01	2.14E−01	2.12E−01
WCP	m^3	3.68E−02	2.14E−02	1.52E−02	1.40E−02

results, is finally made. The linear production system is shown both without allocation (considering by-products as waste to be disposed of) and with allocation (considering by-products as feedstock material for the extended production system), whereas two circular wine production options are taken into account, namely Circular Production system A (CP-A) and Circular Production system B (CP-B), differing in the use of grapeseed oil (CP-A considers grapeseed oil as an ingredient in the production of a biofuel and CP-B considers using grapeseed oil as a food oil product). The avoided productions of citric acid and of diesel (in both CP-A and CP-B), of ethanol (in CP-A) and of soybean oil (in CP-B) are accounted for, due to the assumed substitution of the primary materials with the recovered tartaric acid, biofuel, grapeseed oil for energy or food purposes, respectively. In Table 6 the impacts generated by each system are compared.

It is evident from the figures in Table 6 that the make, use and dispose production option as represented by the linear system, both with and without allocation, has a much higher environmental load than the circular systems. In particular, in the GWP, FEP and MRS impact categories the impacts of the linear system without allocation are three times higher than those of circular systems and more than twice in the remaining impact categories. The benefits of sharing the environmental burdens among the main product and co-products by means of exergetic allocation can be appreciated as in the linear system with allocation the environmental burdens associated to the wine production are reduced in comparison to the linear system without allocation, due to the co-products valorisation. The lower impacts of circular production options, CP-A and CP-B, confirm the environmental benefits of transitioning towards a circular economy. However, circular economy patterns may differ, as CP-A shows a slightly higher environmental burden compared to CP-B depending on the different implementation routes. The option of considering the grapeseed oil for food purposes (CP-B) is more favourable in that, when grapeseed oil is used as a food oil, it has the potential to substitute and avoid the production of soybean oil, that has similar functions, thus preserving large pieces of land for agricultural purposes and reducing the use of fertilizers and pesticides which are required in the production of soybean. The benefits associated with the avoided production of soybean oil are particularly evident in the MEP impact category, where the net impact is negative (−4.40E−05 kg N eq), indicating that the environmental load on this category is completely cancelled by the gained benefit. Furthermore, the benefits deriving from the production of tartaric acid (easily obtained from calcium tartrate), using wine lees as feedstock, are also appreciated through the avoided production of citric acid that comes from citrus fruit. Citric acid is a weak acid, it is an effective preservative for many beverages, whereas tartaric acid has a stronger acidic potential, which means that a lesser quantity is needed. Overall, the avoided production of soybean oil and citric acid is beneficial as they do not compete with food crops and does not imply changes in land use in the long term. Likewise, the reduction of the reliance on fossil energy from the grid, thanks to the bio-based energy recovered from stalks and prunings, is beneficial in further lowering the impacts generated by CP-A and CP-B in GWP and FRS impact categories. Last but not least, it should not be disregarded that grapeseed oil for food purposes, in addition to the above mentioned smaller impacts, generates a higher market value than when it is converted into an energy carrier.

When assessing a production process, the sources of impacts and criticalities must be carefully identified in order to define potentials for an improved environmental performance (Corcelli et al., 2018). The LCA of the investigated system pinpointed the environmental hotspots related to the different production processes and highlighted the benefits that can be achieved if co-products are used as feedstock material for a biorefinery instead of being considered as waste in a linear production system. At first, the linear production of wine as the main product needed a careful analysis to understand the contribution of each input in each phase to the selected impact categories. The linear production system (Subsystem 1) confirmed similar results reported by Meneses et al. (2016) on a previous study on red grapes in Catalonia, Spain. One of the ways to reduce the environmental impacts of the agricultural phase is to practise organic farming. This can be done by replacing fossil-based fertilizers with nutrient-containing organic waste derived from grape stalks, exhausted pomace and prunings as manure/compost (Ahmad et al., 2020). Another option to reduce the environmental loads of the agricultural phase is to use biofuels (FAEE) instead of diesel, as shown in the previous section, although the further processing of grapeseed oil through a transesterification process to meet energy demands in the agricultural phase resulted to produce higher environmental impacts compared to when grapeseed oil is used as a food product. To a certain extent, this addresses the ongoing debate on food *versus* biofuels by avoiding the expansion of cropland to biofuel production (Searchinger et al., 2008). In the vinification phase, the environmental loads are mainly due to the use of electricity to power the grape pressing machines, to the water consumption and to the use of hydrogen hypochloride as a disinfectant. Electricity consumption can significantly be reduced by using more efficient operating machines or by using heat from steam generated from grape prunings or exhausted pomace biomass or other renewable energy sources, such as solar and wind. Concerning the bottling phase, the glass production for wine packaging is of major concern to the environment as it requires electricity consumption and primary natural resources. A sustainable possible solution is to replace glass packaging with another material or to use recycled glass or to substitute the glass bottle with an aseptic carton as proposed by Meneses et al. (2016), although this alternative would require an impact analysis on the chemical and flavor characteristics of the wine.

Overall, diesel, fertilizers, pesticides, electricity, glass bottles, disinfectants and water consumption were identified as hotspots of the linear production system. Therefore, any environmental management programmes that aim to generate substantial improvements to wine's environmental profile should focus on these inputs.

Furthermore, combined potential benefits of the valorisation of winery co-outputs, such as grape pomace and wine lees, have revealed important environmental improvement options for the wine industry. An extended production encompassing biorefinery scenario was explored in this study and the results have certainly confirmed the environmental advantages that can be achieved by extracting useful bio-based products such as grapeseed oil, calcium tartrate and by-products such

Table 7
Results of the Monte Carlo uncertainty analysis referred to a functional unit of 1 bottle of Asprinio wine in the CP-B scenario.

Impact category	Unit	Mean	Median	SD	CV%	SEM
GWP	kg CO_2 eq	5.25E−01	5.25E−01	2.42E−02	4.61%	7.65E−04
PMFP	kg $PM_{2.5}$ eq	1.37E−03	1.36E−03	7.38E−05	5.39%	2.33E−06
TAP	kg SO_2 eq	3.88E−03	3.88E−03	1.66E−04	4.28%	5.26E−06
FEP	kg P eq	1.80E−04	1.64E−04	9.23E−05	51.4%	2.92E−06
MEP	kg N eq	−4.61E−05	−4.48E−05	1.14E−05	24.7%	3.60E−07
HTP_c	kg 1,4-DCB	1.60E−02	1.20E−02	1.70E−02	106%	5.38E−04
MRS	kg Cu eq	2.29E−03	2.28E−03	1.45E−04	6.35%	4.59E−06
FRS	kg oil eq	2.00E−01	1.99E−01	1.36E−02	6.80%	4.31E−04
WCP	m^3	7.60E−03	2.03E−02	1.39E−01	1830%	4.41E−03

prunings, yeast cells and bioethanol from grape pomace and wine lees. Within the biorefinery scenario of obtaining grapeseed oil (side production chain 1), electricity was identified as a potential drawback. The process of extracting grapeseed oil is largely mechanical and uses small amounts of chemicals, but the machines need to run on electricity and therefore other sources of renewable power need to be identified as well as the use of biomass residues, such as stalks and grape prunings, to provide heat. Grapeseed oil production through the biorefinery can lead to the avoided soybean oil production as both oils can perform the same functions as cooking oils. This replacement has the potential to preserve large pieces of land meant for soybean farming and the land can be used for other crops to ensure food security.

With regards to the scenario of obtaining calcium tartrate from wine lees (side production chain 2), it can be noted that heat from steam and electricity are the major techno-spherical inputs that may jeopardize and affect the positive intensions of establishing a biorefinery at the plant. It is therefore suggested in this study to use the available grape prunings to produce the steam required in the distillation processes to counter this threat and the achieved results are encouraging. The value-added conversion of the bio-products, such as grapeseed oil, tartaric acid and other by-products from winemaking, can surely help in reducing the negative environmental costs towards a more pronounced sustainability of the winemaking industry. Italy is one of the leading wine producers in the world. By adopting the suggested improvements, its wine industry may become a leading example of a circular winery industry. Nevertheless, in order to implement an upgrade of wineries to a biorefinery concept at an industrial scale, it is necessary to involve all the stakeholders, such as wine producers, academics, investors and local communities to undertake further pilot plant trials and assess them through life cycle analysis and feasibility studies. The results of this study are a first step in this direction, indicating that, if the annual production of Italian wine is considered, namely 5.48 billion L in 2018 (OIV, 2019), an yearly emission saving of 9.6E+09 kg CO_2 eq could be achieved at the large scale of global production, by implementing a circular production pattern instead of a linear one. This would translate into a virtual reforestation of about 2.13E+06 ha/yr, at an assumed average net primary production of 1.5 t C/ha forest/year (Kloeppel et al., 2007), *i.e.* about twice the surface of the Campania Region.

4.2. Uncertainty analysis

The benefits of adding circular patterns through system expansion were explored in this study and the LCA results indicated a better performance of the circular production option CP-B, in which grapeseed oil is directed towards the market for food purposes, cosmetics or medical application. However, the uncertainty of the results exists, due to several factors including quality of data, assumptions made in building scenarios, allocation choices, system boundaries and methods used for impact assessment, thus affecting the overall results of the LCA study (Cellura et al., 2011). In this framework, a Monte Carlo simulation was performed to analyse the parameter uncertainty, related to data quality, as the main source of uncertainty in this LCA study. In particular, the uncertainty evaluation was applied to the most performant scenario to test the reliability and robustness of its results.

The Monte Carlo approach is the most commonly used uncertainty propagation method, that replaces point estimates with random numbers, thousands of times, using each time a different set of random values, obtained from probability density functions (Huijbregts, 1998). In this study, the Monte Carlo simulation was implemented by means of the SimaPro 9.0.0.49 software, considering a sample size of 1000 trials and assigning a log-normal distribution for both background input flows from the EcoInvent v.3.5 database and foreground data.

Table 7 shows the results, expressed in terms of expected values and lower and upper bounds of the 95% confidence interval, for each midpoint impact category considered, referred to a functional unit of 1 bottle of Asprinio wine in the CP-B scenario. For each selected category, the mean, median, standard deviation (SD), coefficient of variation (CV, defined as the ratio between the SD and the absolute value of the mean) and standard error of the mean (SEM, defined as the standard deviation of the sampling distribution of the mean) are indicated. The negative values of mean and median for the MEP impact category are in line with the results shown in Table 6, indicating a net environmental benefit. CV is lower than 6.80% in most of the impact categories, namely GWP, PMFP, TAP, MRS, FRS, and lower than 51.4% in MEP and FEP impact categories. Such a range of values is regarded as a lower variation, thus confirming the reliability of data used in these categories (Beccali et al., 2010). Conversely, HTP_c and WCP are characterized by an uncertainty range above 100%, due to the uncertainty of both EcoInvent background data and of the characterization factors of the selected method (Benini et al., 2014). A deeper insight into these impact categories may be needed in order to reduce the overall uncertainty of the achieved results.

5. Conclusions

In this study, the main goal was the evaluation of the environmental performance of a wine production system by means of LCA, that has been proved to be capable of assessing symbiosis and/or resource sharing patterns, where waste and by-products (energy and material flows) are reused. As a first step, the main hotspots of a traditional production system were identified and the bottling phase, in particular the production of packaging glass, resulted to contribute with the highest environmental load. The LCA results indicated human carcinogenic toxicity, freshwater eutrophication and fossil resource scarcity impact categories as the most affected ones. As a second step, a framework for developing circular patterns was explored, by assessing the conversion of co-outputs into value-added bio-products, such as grapeseed oil, calcium tartrate, yeast cell, bioethanol and antioxidants, and their reuse in the production system to close the loops. The LCA results of the investigated circular production systems demonstrated a reduction of the negative impacts associated to the winemaking sector, especially for the global warming, freshwater eutrophication and mineral resource scarcity impact categories. The achieved results showed that there are relevant improvement potentialities within the winery segment. Within the agro-food sector, the exploitation of organic waste residues is crucial, but, at the same time, it requires an appropriate evaluation on a case-by-case basis (Fiorentino et al., 2019; Ahmad et al., 2020). The wine industry is one of the most important food and beverage industry of the world and Italy plays a leading role in wine production globally. Wineries produce huge amounts of waste which offer a cheap feedstock material, in the frame of the biorefinery model and circular economy, which may be exploited for the production of chemicals and energy, thus contributing to the sustainability of the agro-food production chain. As we enter the decade to deliver on the UN Sustainable Development Goals (SDGs) and climate action, there is an emerging consensus that circular economy solutions are critical to achieve those goals by the 2030 deadline (WEF, 2020). Based on this case study, the winery industry can actually shift from linear production systems to circular systems, in a biorefinery perspective, with the aim of contributing to the SDGs. For making it possible, some key factors are strongly needed, such as the development of new technologies and processes, the identification of renewable feedstock not in competition with other production chains (such as winery waste for example), the creation of new markets and competitiveness, the involvement of all the winery industry stakeholders in Italy and, in particular, in the Campania Region, based on the understanding of the potential benefits, both environmental and economic, deriving from the reuse of winery wastes and by-products. In doing so, an innovative bioeconomy model based on the sustainable use of renewable resources in agriculture and industry would be implemented, aiming at biodiversity and environmental protection.

CRediT authorship contribution statement

A. Ncube: Formal analysis, Investigation, Validation, Writing – original draft. **G. Fiorentino:** Formal analysis, Investigation, Validation, Supervision, Writing – review & editing. **M. Colella:** Data curation, Formal analysis. **S. Ulgiati:** Conceptualization, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Ahmad, B., Yadav, V., Yadav, A., Rahman, M.U., Yuan, W.Z., Li, Z., Wang, X., 2020. Integrated biorefinery approach to valorize winery waste: a review from waste to energy perspectives. Sci. Total Environ. 719, 137315. https://doi.org/10.1016/j.scitotenv.2020.137315.

Alba, D.F., Campigotto, G., Cazarotto, C.J., dos Santos, D.S., Gebert, R.R., Reis, J.H., Souza, C.F., Baldissera, M.D., Gindri, A.L., Kempka, A.P., Palmer, E.A., Vedovatto, M., Da Silva, A.S., 2019. Use of grape residue flour in lactating dairy sheep in heat stress: effects on health, milk production and quality. J. Therm. Biol. 82, 197–205. https://doi.org/10.1016/j.jtherbio.2019.04.007.

Aresta, M., Dibenedetto, A., Dumeignil, F., 2015. Biorefineries: An Introduction. De Gruyter, Boston.

Bamber, N., Turner, I., Arulnathan, V., LI, Y., Ershadi, S.Z., Smart, A., & Pelletier, N., 2020. Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations. Int. J. Life Cycle Assess. 25, 168–180. https://doi.org/10.1007/s11367-019-01663-1.

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2010. Life cycle assessment of Italian citrus-based products. Sensitivity analysis and improvement scenarios. J. Environ. Manag. 91, 1415–1428.

Benini, L., Mancini, L., Sala, S., Manfredi, S., Schau, E.M., Pant, R., 2014. Normalisation Method and Data for Environmental Footprints. European Commission, Joint Research Center. Institute for Environment and Sustainability, Publications Office of the European Union, Luxemburg ISBN: 978-92-79-40847-2.

BIT, 2019. Italian bioeconomy strategy intergrating sectors, systems and institutions. Retrieved from. https://ec.europa.eu/research/bioeconomy/pdf/bit_en_strategy_2019.pdf.

Cappellini, M., 2019. Towards VINITALY-Italian wine invoices 11 billion Italy, the world's leading producer. Retrieved February 26, 2020, from. https://www.ilsole24ore.com/art/il-vino-italiano-fattura-11-miliardi-italia-primo-produttore-mondiale-ABAdqbkB?refresh_ce=1.

Cellura, M., Longo, S., Mistretta, M., 2011. Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile. Renew. Sustain. Energy Rev. 15 (9), 4697–4705.

Chiriacò, M.V., Belli, C., Chiti, T., Trotta, C., Sabbatini, S., 2019. The potential carbon neutrality of sustainable viticulture showed through a comprehensive assessment of the greenhouse gas (GHG) budget of wine production. J. Clean. Prod. 225, 435–450. https://doi.org/10.1016/j.jclepro.2019.03.192.

Corbin, K., Hsieh, Y.S., Betts, N., Burton, R.A., 2015. Grape marc as a source of carbohydrates for bioethanol: chemical composition, pre-treatment and saccharification. Bioresour. Technol. 193, 76–83. https://doi.org/10.1016/j.biortech.2015.06.030.

Corcelli, F., Fiorentino, G., Vehmas, J., Ulgiati, S., 2018. Energy efficiency and environmental assessment of papermaking from chemical pulp — a Finland case study. Clean. Prod. 198, 96–111. https://doi.org/10.1016/j.jclepro.2018.07.018.

Cortés, A., Moreira, M.T., Feijoo, G., 2019. Integrated evaluation of wine lees valorization to produce value-added products. Waste Manag. 95, 70–77.

Cortés, A., Oliveira, L.F.S., Ferrari, V., Taffarel, S.R., Feijoo, G., Moreira, M.T., 2020. Environmental assessment of viticulture waste valorisation through composting as a biofertilisation strategy for cereal and fruit crops. Environ. Pollut. 264, 114794. https://doi.org/10.1016/j.envpol.2020.114794.

Devesa-Rey, R., Vecino, X., Varela-Alende, J., Barral, M.T., Cruz, J.M., Moldes, A.B., 2011. Valorization of winery waste vs. the costs of not recycling. Waste Manage. 31 (11), 2327–2335. https://doi.org/10.1016/j.wasman.2011.06.001.

Dimou, C., Koutelidakis, A., 2016. Grape pomace: a challenging renewable resource of bioactive phenolic compounds with diversified health benefits. Food Process. Technol. 3 (1), 262–265. https://doi.org/10.15406/mojfpt.2016.03.00065.

Ecoinvent. (2020, April 29). Ecoinvent. Retrieved from Ecoinvent: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/system-models-in-ecoinvent-3.html.

Ellen Macarthur Foundation, 2015. Towards a circular economy: business rationale for an accelerated transition. ellenmacarthurfoundation.org. Retrieved June 12, 2020, from. https://www.ellenmacarthurfoundation.org/assets/downloads/TCE_Ellen-MacArthur-Foundation-9-Dec-2015.pdf.

EPO. (2020, February 25). Retrieved from European Patent Office: https://www.epo.org/index.html.

European Biofuels Technology Platform, 2011. Fatty acid methyl esters (FAME)-biofuel fact sheet. European Biofuels Technology Platform. Retrieved August 24, 2020, from. https://www.etipbioenergy.eu/fact-sheets/fatty-acid-methyl-esters-fame-fact-sheet.

European Commission, 2018a. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy https://doi.org/10.2777/792130 Brussels, Belgium.

European Commission, 2018b. Innovative biomaterials production from wine industry waste. Retrieved from VEGEA SRL-Horizon 2020:. https://cordis.europa.eu/project/rcn/215862/factsheet/en.

European Commission, 2020. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A New Circular Economy Action Plan — For a Cleaner and More Competitive Europe Brussels, Belgium: COM/2020/98 final.

FAO, 2011. Global food losses and food waste-extent, causes and prevention. Düsseldorf, Germany: FAO. Retrieved September 10, 2019, from. https://ec.europa.eu/knowledge4policy/publication/global-food-losses-food-waste-extent-causes-prevention_en.

FAO, 2018. Assessing the Contribution of Bioeconomy to Countries's Economy—A Brief Review of National Frameworks. Food and Agriculture Organization of the United Nations, Roma Retrieved November 11, 2019.

Ferrara, C., De Feo, G., 2018. Life cycle assessment application to the wine sector: a critical review. Sustainability 10 (2), 395. https://doi.org/10.3390/su10020395.

Ferri, M., Vannini, M., Ehrnell, M., Eliasson, L., Xanthakis, E., Monari, S., Tassoni, A., 2020. From winery waste to bioactive compounds and new polymericbiocomposites: a contribution to the circular economy concept. J. Adv. Res. 24, 1–11. https://doi.org/10.1016/j.jare.2020.02.015.

Fiorentino, G., Ripa, M., Ulgiati, S., 2017. Chemicals from biomass: technological versus environmental feasibility. A review. Biofuels Bioprod. Bioref. Energy Fuels 11 (1), 195–214. https://doi.org/10.1002/bbb.1729.

Fiorentino, G., Zucaro, A., Ulgiati, S., 2019. Towards an energy efficient chemistry. Switching from fossil to bio-based products in a life cycle perspective. Energy 170, 720–729. https://doi.org/10.1016/j.energy.2018.12.206.

Garavaglia, J., Markoski, M.M., Oliveira, A., Marcadenti, A., 2016. Grape seed oil compounds: biological and chemical actions for health. Nutr. Metab. Insights 9, 59–64. https://doi.org/10.4137/NMI.S32910.

Garcia-Gonzalez, L., Bijttebier, S., Voorspoels, S., Uyttebroek, M., 2015. Cascaded valorization of food waste using bioconversions as core processes. Advances in Food Biotechnology. Wiley Online Library, New York, pp. 427–442 https://doi.org/10.1002/9781118864463.ch26.

Gnansounou, E., 2017. Chapter 2: Fundamentals of life cycle assessment and specificity of biorefineries. Life-Cycle Assessment of Biorefineries , pp. 41–75 Lausanne, Switzerland. https://doi.org/10.1016/B978-0-444-63585-3.00002-4.

Gobert, J., 2019. Biorefineries as models of a sustainable socio-technical transition? Ital. J. Sci. Technol. Stud. 10, 30–46 Retrieved from. hal-enpc.archives-ouvertes http://www.tecnoscienza.net/index.php/tsj/article/view/378/234.

Goedkoop, M., Heijungs, R., Huijbregts, M., DeSchryver, A., Struijs, J., VanZelm, R., 2009. ReCiPe 2008 — a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation. Den Haag https://doi.org/10.13140/RG.2.1.4872.6640.

Goedkoop, M., Oele, M., Tomm, J.L., 2016. Introduction to LCA with SimaPro. Creative Commons Attribution-Noncommercial-Share Alike Retrieved November 6, 2019, from. www.pre-sustainability.com http://creativecommons.org/.

Gómez-Brandón, M., Lores, M., Insam, H., Dominguéz, J., 2019. Strategies for recycling and valorization of grape marc. Crit. Rev. Biotechnol. 39, 437–450. https://doi.org/10.1080/07388551.2018.1555514.

Gontard, N., Sonesson, U., Birkved, M., Majone, M., Bolzonella, D., Celli, A., 2018. A research challenge vision regarding management of agricultural waste in a circular bio-based economy. Crit. Rev. Environ. Sci. Technol. 48 (6), 614–654. https://doi.org/10.1080/10643389.2018.1471957.

Gullón, B., Gullón, P., Eibes, G., Cara, C., De Torres, A., López-Linares, J., Ruiz, E., 2018. Valorisation of olive agro-industrial by-products as a source of bioactive compounds. Sci. Total Environ. 645, 533–542. https://doi.org/10.1016/j.scitotenv.2018.07.155.
Hang, Y.D., Woodams, E.E., 2008. Methanol content of grappa made from New York grape pomace. Bioresour. Technol. 99 (9), 3923–3925. https://doi.org/10.1016/j.biortech.2007.07.065.
HaproWine, 2013. Integrated waste management and life cycle assessment in the wine industry Issue. Retrieved September 13, 2019, from. www.haprowine.eu.
Harris, S., Martin, M., Diener, D., 2021. Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustain. Prod. Consumpt. 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.
Harsha, P., Gardana, C., Simonetti, P., Spigno, G., Lavelli, V., 2013. Characterization of phenolics, in vitro reducing capacity and anti-glycation activity of red grape skins recovered from winemaking by-products. Bioresour. Technol. 140, 263–268. https://doi.org/10.1016/j.biortech.2013.04.092.
Huijbregts, M.A.J., 1998. Application of uncertainty and variability in LCA. Int. J. Life Cycle Assess. 3, 273–280.
Iannone, R., Miranda, S., Riemma, S., De Marco, I., 2016. Improving environmental performances in wine production by a life cycle assessment analysis. J. Clean. Prod. 111, 172–180. https://doi.org/10.1016/j.jclepro.2015.04.006.
ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework.
ISO 14044, 2006. Environmental Management – Life Cycle Assessment – Requirements and Guidelines.
Jourdaine, M., Loubet, P., Trebucq, S., Sonnemann, G., 2020. A detailed quantitative comparison of the life cycle assessment of bottled wines using an original harmonization procedure. J. Clean. Prod. 250 (119472). https://doi.org/10.1016/j.jclepro.2019.119472.
JRC, 2010. International Reference Life Cycle Data System (ILCD) Handbook – General Guide for Life Cycle Assessment – Detailed Guidance (Luxembourg. Edit by European Commission and Institute for Environment and Sustainability).
Kloeppel, B.D., Harmon, M.E., Fahey, T.J., 2007. Estimating aboveground net primary productivity in forest-dominated ecosystems. In: Fahey, T.J., Knapp, A.K. (Eds.), Principles and Standards for Measuring Primary Production. Oxford University Press, New York, pp. 63–81 268 pp.
Kopsahelis, N., Dimou, C., Papadaki, A., Xenopoulos, E., 2018. Refining of wine lees and cheese wheyfor the production of microbial oil,polyphenol-rich extracts and value-addedco-products. Chem. Technol. Biotechnol. 93, 257–268. https://doi.org/10.1002/jctb.5348.
Manso, T., Gallardo, B., Salvá, A., Guerra-Rivas, C., Mantecón, A.R., Lavín, P., Fuente, M.A., 2016. Influence of dietary grape pomace combined with linseed oil on fatty acid profile and milk composition. J. Dairy Sci. 99, 1111–1120. https://doi.org/10.3168/jds.2015-9981.
Manzone, M., Paravidino, E., Bonifacino, G., Balsari, P., 2016. Biomass availability and quality produced by vineyard management during a period of 15 years. Renew. Energy 99, 465–471. https://doi.org/10.1016/j.renene.2016.07.031.
Martinez, G., Rebecchi, S., Decorti, D., Domingos, J., Natolino, A., Del Rio, D., Bertin, L., Da Porto, C., Fava, F., 2016. Towards multi-purpose biorefinery platforms for the valorisation of red grape pomace: production of polyphenols, volatile fatty acids, polyhydroxyalkanoates and biogas. Green Chem. 1. https://doi.org/10.1039/C5GC01558H.
Martins, A., Araújo, A., Graca, A., Caetano, N., Mata, S., Teresa, M., 2018. Towards sustainable wine: comparison of two Portuguese wines. J. Clean. Prod. 183, 662–676. https://doi.org/10.1016/j.jclepro.2018.02.057.
Massey, R. (2015, August 25). Chemistry World. Retrieved 2019, from Chemistry World: https://www.scientificamerican.com/article/new-method-turns-tons-of-wine-waste-into-useful-chemicals/.
Mateo, J.J., Maicas, S., 2015. Valorization of winery and oil mill wastes by microbial technologies. Food Res. Int. 73, 13–25. https://doi.org/10.1016/j.foodres.2015.03.007.
Meneses, M., Torres, C.M., Castells, F., 2016. Sensitivity analysis in a life cycle assessment of an aged red wine production from Catalonia, Spain. Sci. Total Environ. 562, 571–579. https://doi.org/10.1016/j.scitotenv.2016.04.083.
Merli, R.P., Preziosi, M., Acampora, A., 2017. Sustainability experiences in the wine sector: toward the development of an international indicators system. J. Clean. Prod. 172, 3791–3805. https://doi.org/10.1016/j.jclepro.2017.06.129.
Muhlack, R., Potumarthi, R., Jeffery, D., 2018. Sustainable wineries through waste valorisation: a review of grape marc utilisation for value-added products. Waste Manag. 72, 99–118.
Nayak, A., Bhushan, B., Rodriguez-Turienzo, I., 2018. Recovery of polyphenols onto porous carbons developed from exhausted grape pomace: a sustainable approach for the treatment of wine wastewaters. Water Res. 145, 741–756. https://doi.org/10.1016/j.watres.2018.09.017.
Nierenberg, C. (2017, July 21). LiveScience. The science of cooking oils: which are really the healthiest? Retrieved 12 01, 2020, from https://www.livescience.com/59893-which-cooking-oils-are-healthiest.html.
Nieuwlaar, E., Roes, A.L., Patel, M.K., 2015. Final energy requirements of steam for use in environmental life cycle assessment. Indust. Ecol. 20, 828–836.
Oele, M. (2019, November 20). SimaPro. Retrieved from SimaPro: https://simapro.com/2019/whats-new-in-simapro-9-0/.
OIV, 2019. Statistical report on world vitiviniculture. Retrieved October 23, 2019, from. http://www.oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf.
Palaa, M., Kantarli, I., Buyukisik, H., Yanik, J., 2014. Hydrothermal carbonization and torrefaction of grape pomace: a comparative evaluation. Bioresour. Technol. 161, 255–262. https://doi.org/10.1016/j.biortech.2014.03.052.
Papadaki, G., Mantzouridou, F., 2019. Citric acid production from the integration of Spanish-style green olive processing wastewaters with white grape pomace by Aspergillus niger. Bioresour. Technol. 280, 59–69. https://doi.org/10.1016/j.biortech.2019.01.139.
Petti, L., Arzoumanidis, I., Benedetto, G., Bosco, S., Cellura, M., De Camillis, C., 2015. Life cycle assessment in the wine sector. Life Cycle Assessment in the Agri-food Sector: Case Studies, Methodological Issues and Best Practices. Springer, pp. 123–184 https://doi.org/10.1007/978-3-319-11940-3_3.
Poveda, J., Loarce, M., Alarcon, M., Diaz-Maroto, M., 2018. Revalorization of winery by-products as source of natural preservatives obtained by means of green extraction techniques. Ind. Crop. Prod. 112, 617–625. https://doi.org/10.1016/j.indcrop.2017.12.063.
Puglia, M., Pedrazzi, S., Allesina, G., Morselli, N., Tartarini, P., 2017. Vine prunings biomass as fuel in wood stoves for thermal power production. Int. J. Heat Technol. 35, 96–101. https://doi.org/10.18280/ijht.35Sp0113.
Ripa, M., Buonaurio, C., Mellino, S., Fiorentino, G., Ulgiati, S., 2014. Recycling waste cooking oil into biodiesel: A life cycle assessment. Int. J. Performability Eng. 10, 347–356.
Ruberto, G., Renda, A., Amico, V., Tringali, C., 2008. Volatile components of grape pomaces from different cultivars of Sicilian Vitis vinifera L. Bioresour. Technol. 99 (2), 260–268. https://doi.org/10.1016/j.biortech.2006.12.025.
Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., ... Yu, T.H., 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science 319 (5867), 1238–1240. https://doi.org/10.1126/science.1151861.
Sivaramakrishnan, K., 2011. Determination of higher heating values of biofuels. Int. J. Eng. Sci. Technol. 7981–7987.
Szargut, J., Morris, D.R., Steward, F.R., 1988. Exergy Analysis of Thermal, Chemical, and Metallurgical Processes. Hemisphere Publishing Corporation, New York.
Vezzoli, C., 2018. Design for Environmental Sustainability: Life Cycle Design of Products. 2nd ed. Springer, London ISBN 9781447173649.
WEF. (2020, January 22). World Economic Forum. Retrieved February 25, 2020, from https://www.weforum.org/agenda/2020/01/the-world-needs-a-circular-economy-lets-make-it-happen/.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno, R., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.
Zabaniotou, A.K., Kamaterou, P., Pavlou, A., Panayiotou, C., 2018. Sustainable bioeconomy transitions: targeting value capture by integrating pyrolysis in a winery waste biorefinery. J. Clean. Prod. 172, 3387–3397. https://doi.org/10.1016/j.jclepro.2017.11.077.
Zacharofl, M.-P., 2017. Grape winery waste as feedstock for bioconversions: applying the biorefinery concept. Waste Biomass Valoriz. 8, 1011–1025. https://doi.org/10.1007/s12649-016-9674-2.
Zhang, N., Hoadley, A., Patel, J., Lim, S., Li, C., 2017. Sustainable options for the utilization of solid residues from wine production. Waste Manag. 60, 173–183. https://doi.org/10.1016/j.wasman.2017.01.006.
Zion Market Research, 2017. Global renewable chemicals market size:global industry perspective, comprehensive analysis and forecast, 2016–2022. Retrieved October 14, 2019, from. https://www.zionmarketresearch.com/requestbrochure/renewable-chemicals-market.