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Integrated biorefinery approach to valorize winery waste: A review from waste to energy perspectives

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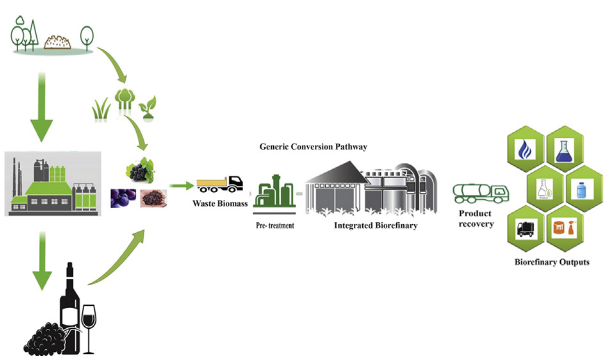
HIGHLIGHTS

- Winery waste can be used as potential feedstock to address global energy demand.
- Sustainable wineries through waste valorization are discussed.
- Emerging approaches for integrated biorefinery are is reviewed.
- Contemporary biorefinery opportunities beyond traditional are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

The ever-increasing environmental crisis, depleting natural resources, and uncertainties in fossil fuel availability have rekindled researchers' attention to develop green and environmentally friendlier strategies. In this context, a biorefinery approach with a zero-waste theme has stepped-up as the method of choice for sustainable production of an array of industrially important products to address bio-economy challenges. Grape winery results in substantial quantities of solid organic and effluent waste, which epitomizes an increasing concentration of pollution problems with direct damage to human health, economy and nature. From the perspective of integrated biorefinery and circular economy, winery waste could be exploited for multiple purpose value-added products before using the biomass for energy security. This review covers state-of-the-art biorefinery opportunities beyond traditional methods as a solution to overcome many current challenges such as waste minimization in grape leaves, stems, seeds, pomace, wine lees, vinasse etc. and the biosynthesis of various high-value bioproducts viz., phenolic compounds, hydroxybenzoic acids, hydroxycinnamic acids, flavonoids, tartaric acids, lignocellulosic substrates etc.. The critical discussion on the valorization of winery waste (solid, liquid, or gaseous) and life cycle assessment was deployed to find a sustainable solution with value added energy products in an integrated biorefinery approach, keeping the environment and circular economy in the background.

Abbreviations: mt, millions of tons; mhl, millions of hectoliters; OIV, International Organization of Vine and Wine; FAO, Food and Agriculture Organization; LCA, Life Cycle Assessment; BHA, Butylated-hydroxyanisole and; BHT, Butylatedhydroxytoluene.

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1. Introduction

The wine industry has received significant importance in the agriculture and agro-industrial sectors around the globe. Grapes are one of the most important fruit crops cultivated worldwide (Gomez-Brandon et al., 2019). The grape production was estimated around 77.8 mt in 2018 (2019 Statistical Report on World vitiviniculture, 2019). According to the FAO statistics, the grape is the leading fruit crop cultivated in the world (Food and Agriculture Organization of the United Nations, 2017). The reports from the International Organization of Vine and Wine (OIV) show that 292 mhl wine was produced worldwide in 2018 (2019 Statistical Report on World vitiviniculture, 2019). Countries like United States, Australia, Italy, Spain, France, and Germany are the leading grape-producing countries (Hussain et al., 2008) and nations like Spain, China, Italy, Turkey, and France collectively contribute 50% of the total wine production worldwide (2019 Statistical Report on World vitiviniculture, 2019). Reports from OIV 2019 state that Europe is the largest producer of grape with 39% global share, followed by Asia, America, and Spain with 34%, 14%, and 11% share, respectively. Grape marc, skin, stalk, and pomace are among the major waste from the winery. Apart from these waste products, a large amount of wastewater, lees, shoots, and some filtrations residue generated form wineries are among the major cause for environmental deterioration (Musee et al., 2007). The production of a large amount of waste in major grape growing states is directly disposed of in open areas, is a source of environmental pollution due to the emanation of volatile organic compounds (VOC), the release of chemical oxygen demand (COD) and free-run juices infiltration (Rondeau et al., 2013). Vinasse is a winery waste having complex effluents with diverse physicochemical properties. Mostly vinasses are used for irrigation or discharged into aquatic bodies. Due to the presence of recalcitrant compounds and organic acid, the use of untreated vinasse is a serious threat to the environment. The high toxicological effects of winemaking by-products have been reported on terrestrial plants and aquatic organisms even at high dilutions levels. This rationalizes the need for proper treatment of winery by-products before discharge or reuse (Sousa et al., 2019). Regardless of the big pollution source and environmental problem, the wine industry has never been criticized and viewed negatively, because the majority of the wine producers are involved in selling it to the energy industry, composting and dumping. Winery sector produces a large volume of underutilized by-products, which can be a good source if exploited for the extraction of industry-based products (Amulya et al., 2015; Ping et al., 2011a; Spigno and De Faveri, 2007). Studies have demonstrated that winery waste could be a good alternative with immense potential to produce many bioproducts (Fig. 1). Traditionally, the products were limited to fertilizer, dye and food industries, which have now been diversified and an array of products could be generated from winery waste including antimicrobial compounds, food additives, biofuels, functional food, dietary supplement, nutraceuticals, medical remedies, animal feed, and cosmetics (Fig. 1). The mounting need for energy and waste valorization via environmentally friendly processes are forcing to shift from general practices to sustainable circular approaches (Mohan et al., 2016). In the last few years, an integrated biorefinery approach is recognized as a noteworthy solution for the valorization of winery waste (Ky and Teissedre, 2015). In addition, it could potentially be helpful to address environmental problems and a better option for a socio-economic perspective. An integrated biorefinery is considered a better choice over the traditional biorefinery because of its wider utilization of multiple products. The major solid type by-products generated from the winery are stalk, skin, marc, vine shoot, and seeds (Zheng et al., 2012). Other processing products include filtration residue, sludge, wine lees, and a large amount of winery wastewater (Pain and Hepherd, 1985). The traditional utilization of wine pomace is limited to the production of alcohol, food dyes, and fertilizers (Prozil et al., 2012) while the grape seeds are utilized for the extraction of edible seed oil. Currently, the byproducts of the winemaking process became valuable raw feedstock's material for the production of various food additives, functional food, dietary supplement, animal feed, cosmetics and pharmaceutical products (Fig. 1). In contrast to the current state-of-the-art practices, waste generated from wine industries could be valorized for proper socioeconomic benefits, which suit to better environmental conditions. Considering a sharp increase in energy prices, the demand for green materials, biofuels, bioethanol, and energy are particularly compelling in areas of high energy costs, which can be reduced significantly by utilization of winery waste for energy sources. The development of integrated biorefinery from the conventional biorefinery system can be an attractive alternative for various valuable product generation by the processing of winery by-products as raw materials. An integrated biorefinery is continuously emerging with different technologies that enable the conversion of waste in a throng of economically important products and different forms of energy with minimal waste and emission (Fatih Demirbas, 2009). In short, at present integrated biorefinery is the most suitable approach in terms of human health, ecosystem balance, climate change and efficient use of resources. From the perspective of environmental damage, the approach to an integrated biorefinery for grape bioproduct utilization becomes a need for a profitable economy and waste to energy perspectives. Therefore, the scientific aim of the manuscript is to thoroughly address the global grape winery wastes issues with sustainable solutions in an integrated biorefinery approach keeping the environment and circular economy in the background.

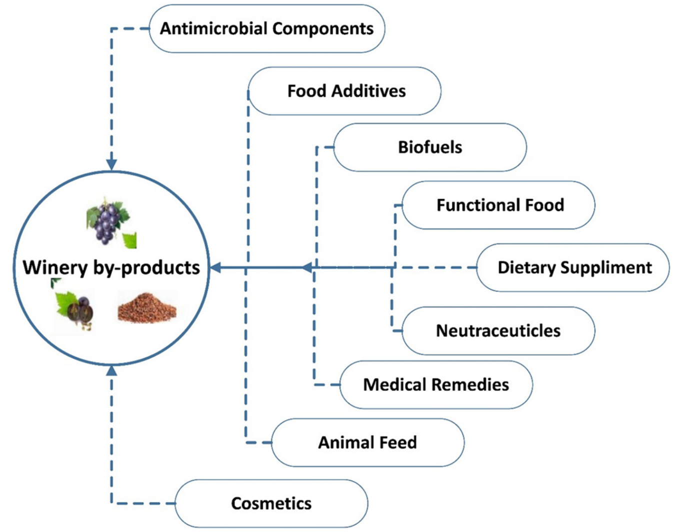

Fig. 1. Utility and significance of By-products obtained from winery waste.

2. Wine waste and value-added products opportunities

The production figures make this crop as a top fruit crop from a production point of view (Poveda et al., 2018) according to the OIV statistical report 2019 the total world grape production was 77.8 mt of which 57% of total grape produce was wine grapes, 36% table grapes and 7% dried grape (Statistical Report on World vitiviniculture, 2019). The majority parts of the total production volume are utilized by wine production industries (Food and Agriculture Organization of the United Nations, 2017). The wine industry generates several by-products and waste material (Devesa-Rey et al., 2011) which consists of high contents of biodegradable compounds (Table S1) and suspended solids (Navarro et al., 2005). Fig. 2 shows the production of different by-products at different levels of wine production. The demand for organic winery waste is growing and associated products are still in the developmental phase and more research is required (Bustamante et al., 2008a; Devesa-Rey et al., 2011; Nerantzis and Tataridis, 2006).

2.1. Grape leaves

Grape leaves are primary waste produced by the winery industries during grape collection procedures. Leaves are important residue from the winery industry, while, the assessment of leaves residue is not estimated, generally. The leaves collected from the industries are either dumped at a landfill site or incinerated. The extraction and utilization of phenolics, tannins, lipids, vitamins, flavonols, organic acids, and types of sugar is less studied in grapes waste leaves, and no economical solutions were proposed for proper management (Xia et al., 2010). Some studies suggest the oil and organic acid contents in waste leaves. The content of different organic acid and polyphenols of these leaves has led to its economic importance. The grape wine leaves are used for the food industry and its juice is recommended for antiseptic eyewash.

2.2. Grape stems

The grape stems are removed to reduce its effects on the organoleptic test and excessive astringency before vinification steps. The stem or grape clusters waste can be up to 7% of the raw matter used for processing (Souquet et al., 2000). The grapevine stems are not a part of the vine making process but its production is directly linked with the winemaking process so it is considered as an import winery waste (Souquet et al., 2000). The stems are useless from an economic point of view because no proper utilization methods are scaled up for its economic utilization. Although it is a potential waste for bioactive compounds and has important value for the extraction of essential compounds, it was considered less in comparison to pomace and seed (Alanon et al., 2015; Anastasiadi et al., 2009; Dias et al., 2015). The common use of stems is for animal feed and most of the time, dumped in landfills. The grape stems could have some possible use for extraction of valuable compounds like proanthocyanidins (Llobera and Cañellas, 2007) phenolics like flavan-3-ols, hydroxycinnamic acids, stilbenes, monomeric and oligomeric flavonols (Karvela et al., 2009). The grape stems have 55–80% of moisture content depending on the variety and no significant difference was recorded in red and white varieties. The current knowledge shows it can be better utilized for phytochemical extraction technology and scaling is required for its commercial utilization. The nutritional and phytochemical composition studies are needed to present its suitable importance for the development of innovative products. The grapes are discovered as a great source for better and enriched co-compost. Furthermore, the addition of winery sludge has been recommended by researchers for its potential use in

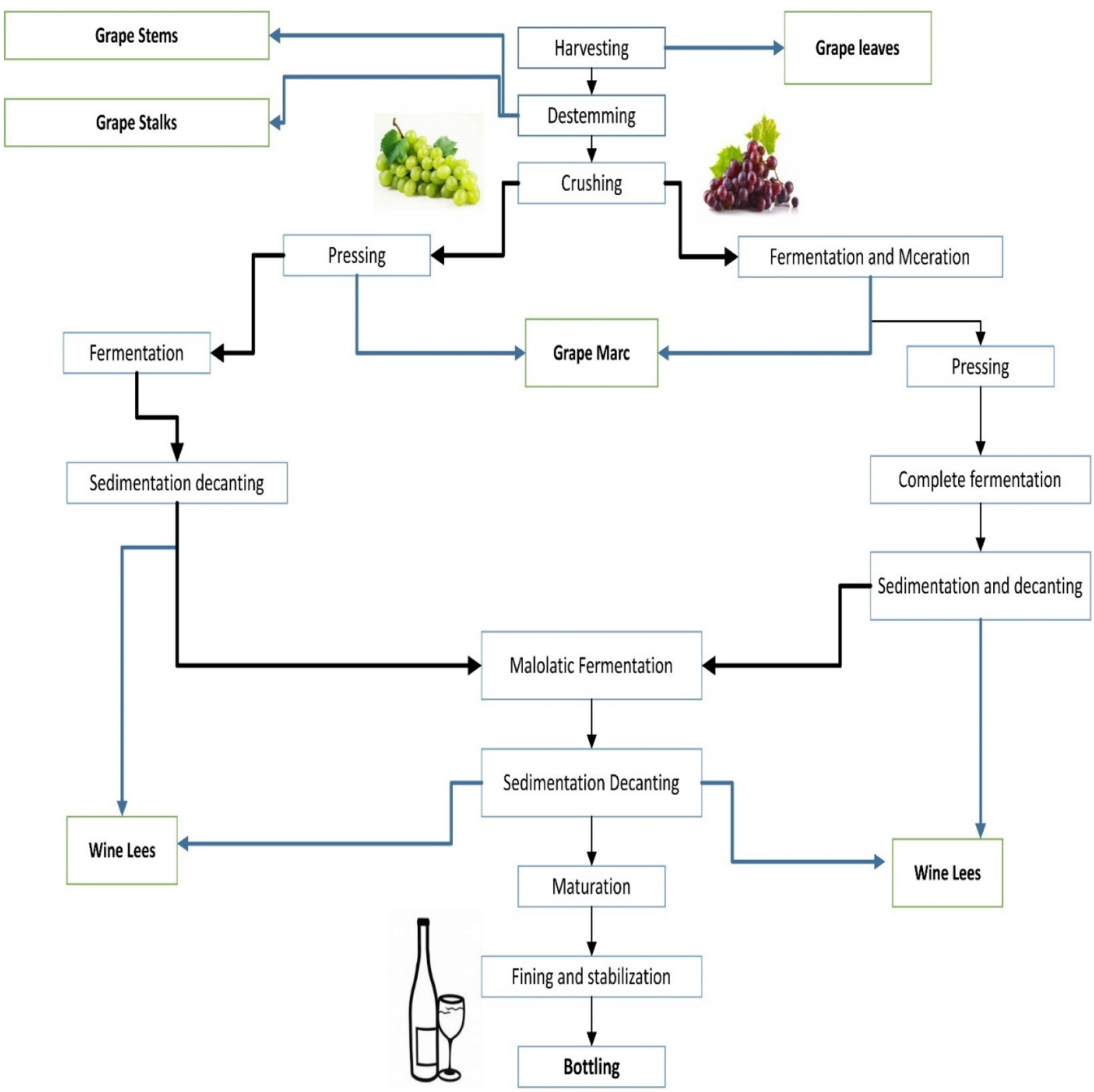

Fig. 2. Different stages of major winery waste production.

agriculture as fertilizer and soil amendment. Additionally, the list of other products recovered from the grape stems, after different treatments, is summarized in Table 1.

2.3. Grape seeds

A large portion of winery waste includes seeds, and it can be up to 30% of the total wet pomace generated during the winemaking process. The seeds contain 25–40% moisture, sugars polysaccharides (36–46%), organic acid (2–7%), oils, and fatty acids (13–20%), phenolics (4–6%), nitrogen substrate (4–6.5%), and minerals. The grape seeds have potential value for their nutraceutical properties (Tuck et al., 2012). The recent studies show a potential extraction for gallic acid, hydroxybenzoic and cinnamic acid derivatives and more important compounds (Lin et al., 2014; Salehi et al., 2019). Besides the nutraceutical properties, some studies show the use of grape seed for anti-cancerous compounds. The number of bioactive compounds can be extracted from seeds that are directly linked with antioxidant properties, which includes grapeseed oil, polyphenols, ethanol, methanol, and xanthan via fermentation, and the production of energy sources (Gonzalez-Paramas et al., 2004), as well as natural antioxidants (Bucic-Kojic et al., 2013).

2.4. Grape pomace

Grape pomace is a solid residue obtained after juice and winemaking. It constitutes a big share of 20% *w*/w of the grapes utilized in wine (Lago-Vanzela et al., 2011; Rubilar et al., 2007; Teixeira et al., 2014a). The fibrous material with skin, seed, and stems from pomace contains a large amount of moisture. The process for making white and red wine is different and the concentration of grape pomace obtained is also different depending on conditions. The red grape pomace can be obtained 2–3 weeks after fermentation starts but in the case of white grapes, it can be obtained right after pressing with pumps. The grape pomace is rich in lignin and cellulose contents ranging from 16.8–24.2% and 27–37%, respectively (Centeno and Stoeckli, 2010). The grape pomace contains skin that can be used to some extent for animal feed but only a few commercial uses are known (Arvanitoyannis et al., 2006a). The grape skin waste extraction represents a different category of a valuable compound containing polyphenols and triterpenes, which can be utilized for nutraceuticals, medical remedies and extract can be utilized for cosmetic industries (Ruberto et al., 2007). The composition of pomace stands for the quality material extraction of different economic compounds. The number of studies have demonstrated high antioxidant content and polyphenol content, suggesting the grape pomace as an important source for natural antioxidants with application in pharmacological, cosmetic, and food industries (Rockenbach et al., 2011). The valuable compounds present in pomace make it a valuable part of byproducts (Table 2). The compounds present in grape pomace can be used as a valorized to food ingredients, chemicals, and biofuels. The cellulose and hemicellulose content in pomace can be used for fermentation and anaerobic digestion for biofuels. The rich content of lignin can be utilized for phenols and blinders.

By its composition, grape pomace has a good scope and number of utilities in various production processes. Grape pomace contains a high amount of seed waste and the relative proportion of seed varies from 38% to 52% of the total dry matter (Ghafoor et al., 2009), although some results are contrasting to the share of seed material (Nawaz et al., 2006) (Fig. 3).

2.5. Wine lees

Wine lees are obtained after the clarification process of winemaking. Wine lees generally collected from the bottom of the container after fermentation be obtained at the bottom of the container after fermentation, as well as it can be collected in the form of residue after filtration or centrifugation. It contributes 5% (*V*/V) of total wine production (Alanon et al., 2011). It falls in the category of microbial biomass which contains a fraction of phenolic compounds, inorganic matter, organic acids and microorganisms (Alanon et al., 2017). A large amount of yeast content has been reported in wine lees. The Lees are important component because it can interact with polyphenol present in wine and contributes a great impact on color and organoleptic properties of wine. The high content of microbes like yeast causes the secretion of enzymes that can boost the hydrolysis and transformation of phenolics. According to information available for chemical composition, lees contains anthocyanins (6–11.7 mg/g × dw (dry weight)) and other phenolics (29.8 mg/g × dw) (Alanon et al., 2011). Mostly, wine lees are disposed of with wastewater but some literature has suggested the use of wine lees for animals feed however, it is not suitable for the user due to poor nutritive value (Maugenet, 1973). Recently Varelas et al. (2016) have reported the first isolation of b-glucan from wine lees, with an environment friendly method.

2.6. Vinasse

The Vinasse is the wastewater generated in the distillery. The source of vinasse is wine lees and grape pomace. It contains part of seed, skin, and dead yeast. Vinasse production is directly linked with alcohol production and called a residue from the distillation unit. Several by-products can be produced from the vinification lees and some products like tartaric acid have good economic importance. Some products could be utilized for different purposes like biocontrol agents, lactic acid, and plant substrate (Table 3).

3. Economical compounds from winery by-products

Grapes are a rich source of different important compounds that can be extracted or isolated after efficient extraction methods using the waste generated from the winery. The remaining waste is demonstrated as a good source of many valuable products. The extraction of these compounds is important to manage the winery waste and generate income. The valorization of waste generated from the winery is one of the extensively studied areas in a sustainable winery approach (Pinelo et al., 2006). The majority of winery waste is an important source of other

Table 1
Methods applied for utilization of Grape stems.

S. No.	Treatments	Products	References
1	Hydrolysis, fermentation; simultaneous saccharification and fermentation of extracted cellulose and hemicellulose	Lactic acid	(Bustos et al., 2004; Bustos et al., 2005; Bustos et al., 2007) (Moldes et al., 2007) (Alonso et al., 2002)
2	Hydrolysis and fermentation	Ferulic acid, p-coumaric acid	(Chen et al., 2018)
3	Pulping process	Cellulose pulp	(Jimenez-Cordero et al., 2014)
4	Solid state fermentation	Food additives	(Sánchez-Moreno et al., 2000)
5	Carbon dioxide activation	Activated carbon	(Nizami et al., 2017)

Table 2
Methods applied for utilization of grape pomace.

S. No.	Processes	Products	References
1	Hydrolysis, fermentation (L. *pentosus*)	Lactic acid	(Portilla Rivera et al., 2007; Portilla et al., 2008)
2	Hydrolysis, fermentation (L. *pentosus*)	Bio-emulsifiers	(Portilla-Rivera et al., 2010)
3	Extraction	Tannins as wood adhesives	(Jiang et al., 2011)
4	Extraction	Polyphenols	(Conde et al., 2011; Ping et al., 2011b; Vatai et al., 2009)
5	Fermentation with *Lactobacillus*	Anti- allergen	(Tominaga et al., 2010)
6	Solid state fermentation	Hydrolytic enzymes	(Díaz et al., 2011)
7	Solid state fermentation	Bioethanol	(Rodríguez et al., 2010)
8	Composting	Plant substrate	(Bustamante et al., 2007; Bustamante et al., 2009; Bustamante et al., 2010; Diaz et al., 2002; Garcia-Lomillo and Gonzalez-SanJose, 2017; Nogales et al., 2005; Pardo et al., 2009)
9	Vermicomposting	Plant substrate	(Paradelo et al., 2009)
10	Composting	Adsorbent	(Paradelo et al., 2009)

useful compounds like fatty acids, and sugars (Devesa-Rey et al., 2011). Apart from these compounds winery waste could be utilized as an alternative source for antioxidants such as butylated-hydroxyanisole (BHA) and butylated hydroxytoluene (BHT), which is good alternate over synthetic products. These compounds are used in the food processing products as a food additive on a large scale. In the recent past, the research was done for scaling up the technology for efficient and environmentally friendly extraction (Barba et al., 2016). The different by-products are extracted using various techniques and the major compounds, source and recent advances in extraction are given below:

3.1. Phenolic acid

Phenolic compounds are an important natural plant product. Phenolic acids are major by-products of the wine industry and much importance has been given for phenolic compounds because of their health benefits, such as antioxidant activity, acting as free radical scavengers, and inhibition of lipoprotein oxidation. It has high economic importance due to great potential as nutraceutical supplements and pharmacological agents. The phenolic compounds, particularly flavanols like catechins and proanthocyanidins have been reported in recent studies (Table S2) (Martins et al., 2016). The major source of derivation is hydroxycinnamic acid and hydroxybenzoic acid having hydroxyl groups and a carboxylic acid at the benzene ring. The phenolics are present mainly in esterified forms as glycosides. The extraction is basically governed by the technology employed and plant waste.

3.2. Hydroxybenzoic acids

The winery waste can be a good source of hydroxybenzoic acid. The major hydroxybenzoic acid derivatives identified in winery waste such as p-hydroxybenzoic acid, protocatechuic acid, tannic acid, vanillic acid, gallic acid derivatives, and syringic acid (Chen et al., 2018; Salehi et al., 2019). The gallic acid is the most abundant hydroxybenzoic acid derivative in stems, skin, and seeds followed by syringic acid in grape stem. Grape seed and pomace from the red varieties have the protocatechuic acid as the most abundant hydroxybenzoic acid (98.65 $mg \cdot g^{-1} \cdot dw$, on average) (Kalli et al., 2018).

3.3. Hydroxycinnamic acids

The major hydrocinnamic acid found in winery waste is caftaric, p-coutaric, and fertaric acids. The profiling of phenolics changes with the method and material used for the extraction. These acids are present in trans-form and some negligible fraction of p-coutaric is present in the trans-form (Anastasiadi et al., 2009). The common result for trans-caffeic acid is recorded in red and white grapes for stems and the maximum amount was recorded over other winery wastes (Apostolou et al., 2013). Furthermore, the data for grape skin shows a critical difference in red and white varieties. The skin was dominated by cis-coutaric acid (Chen et al., 2018; Salehi et al., 2019). Some literature and research showed that hyderxycinnamic acid was not detected in the seed of white grapes. On the other hand, the concentration of 2.90 to

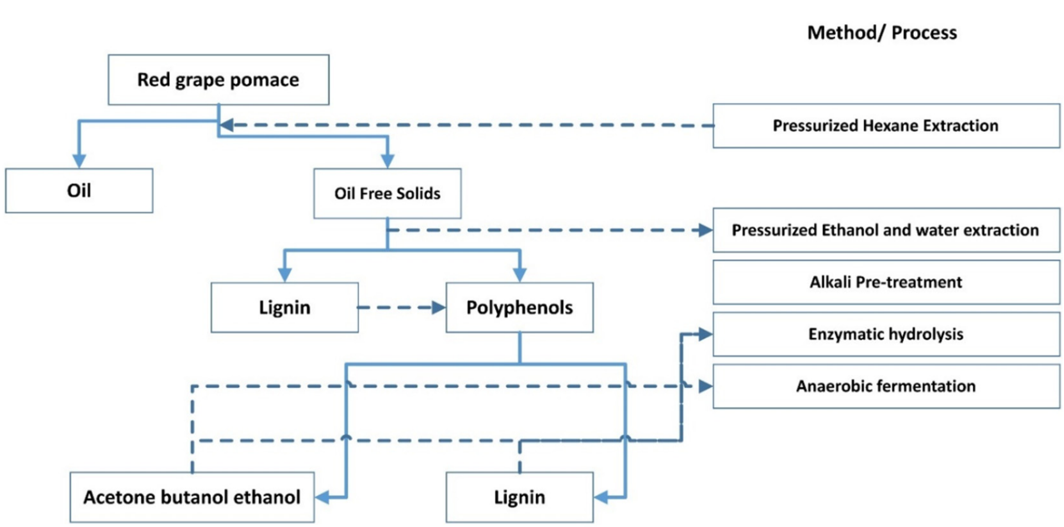

Fig. 3. Integrated process for obtaining different compounds from Red grape pomace.

Table 3
Methods applied for the utilization of grape vinasse or vinification lees.

Residue	Treatment	Product	Reference
Vinasse	Alkali treatment, microwave fermentation	Lactic acid	(Liu et al., 2000)
Vinasse	Solubilization and precipitation	Tartaric acid	(Rivas et al., 2006; Salgado et al., 2010)
Vinasse	Fermentation with *Trichoderma viride*	Biocontrol agent	(Bai et al., 2008)
Vinasse	Fermentation	Protein-rich fungus biomass	(Nitayavardhana and Khanal, 2010)
Vinification lees	No treatment	Nutritional supplement for Lactobacillus	(Bustos et al., 2004; Bustos et al., 2007)
Vinification lees	Extraction of tartaric acid	Nutritional supplement for *Debaryomyces hansenii*	(Salgado et al., 2010)
Lees, grape marc	Yeast-induced fermentation	Protein	(Silva et al., 2011)
Lees, vine shoots, grape stalks, grape marc	Composting	Plant substrate	(Diaz et al., 2002)

6.80 $mg \cdot g^{-1} \cdot dw$ was reported in red grape seeds (Bucic-Kojic et al., 2013).

3.4. Flavonoids

The grape pomace, skin, and seeds are characterized for the good flavonoid content. Flavonoids are structurally low molecular weight compounds, comprised of fifteen carbon atoms (Balasundram et al., 2006). The biosynthesis of flavonols starts during grape development and ripening. The concentration level was recorded significantly higher after 3–4 weeks post-veraison (Mattivi et al., 2006). The physiological processes and harvesting time are major factors influencing the qualitative content in bioactive flavonoids in winery waste (Bavaresco et al., 2007). The flavonoid content comparison shows the flavan-3-ols are in similar concentrations in skins and seeds though the concentration of anthocyanin is more in the skin than other winery waste materials. The industrial residue from the winery has flavanols or flavan-3-ols, anthocyanins, flavonols, flavones, proanthocyanidins and (Garrido and Borges, 2013). The pomace, skin, and seed have demonstrated the potential content of flavonoids (Delgado Adamez et al., 2012; Furiga et al., 2009; Jayaprakasha et al., 2003; Katalinic et al., 2010a; Mattos et al., 2017).

3.5. Tartaric acid

Tartaric acid, a diprotic organic acid, which is mostly used in the winery, food industry, bakery, and pharmaceutical industry as an acidifying agent, taste enhancer and antioxidant. The tartaric acid has a big market, and the demand is high due to its industrial use. Although it is present in several plants but grape waste is considered as a potential source of tartaric acid production. The winery waste wine lees are the most common and useful product for tartaric acid extraction (Muhlack et al., 2018). The studies reported the production of tartaric acid to be 100–150 kg/ton of wine lees. The content depends on different aspects viz., cultivar, cultivation techniques, soil condition, and winemaking process. Recovery for tartaric acid has been well established from winery waste like wine lees and grape marc (Devesa-Rey et al., 2011; Nurgel and Canbas, 1998). A soluble potassium bitartrate is a common form of tartaric acid; however, it is sometimes present as calcium tartrate crystals along with dead yeast, particulate solids and other organic substances. Common recovery method has a high recovery ratio. However, the process is more consuming and complex, expensive, labor-intensive, and environmentally offensive because of the higher quantities of horrible calcium sulfate sludge.

3.6. Lignocellulosic substrates

The grape stalk is the major by-product of the vineyard and it comprises a high degree of fiber and other economic compounds. Other than its use for composting or co-composting with sludge it can be used for extraction of chemical compounds. It was found that the compost generated from the stalks have high nutrient content. Lignocellulose substrate includes hardwood and softwood residues. Somehow little success is achieved in lab scale for its commercial utilization, there are limitations to utilized this on commercial scale. Lignocellulose has been studied for its fiber content, in the form of cellulose, pectin, lignin, etc. (Bilal and Iqbal, 2020; Centeno and Stoeckli, 2010).

4. Environmental impact of winery waste

The wine production has always been considered as environmentally safe; however, past studies have indicated wine grape cultivation and production has severe environmental apprehensions. Although, the wine production has economic and cultural significance attribute across many countries. But the harmful environmental effects related to the whole wine production system must be addressed (Fabbri et al., 2015). The production of wine is gradually increasing and causing more environmental problems (Dimou et al., 2015). The wine industry is associated with several environmental problems, but the few regulations are imposed in comparison to other production industries (Ene et al., 2013; Marshall et al., 2005). Although in the perception, the wine is a safe product (Ruggieri et al., 2009) but past misconceptions may extend the liberty from the environmental laws and regulation (Warner, 2007). The global wine industries are facing major problems with managing organic and solid waste (Barber et al., 2010; Hughey et al., 2005). The solid waste generation is an unavoidable consequence associated with the winery. Organic waste contains by-products like grape marc (Arvanitoyannis et al., 2006a), lees, pomace, stalk, and dewatered sludge. The organic waste is the major reason for strong odors and it's an important reason for proper disposal (Ruggieri et al., 2009). The major environmental problems are directly related to soil, water, and air pollution (Christ and Burritt, 2013). It has been noticed that some wineries are using these organic waste materials as fertilizer by composting and others are selling for energy industries.

The present situation shows that the small-scale wineries still not always abide by the rule and regulations for proper disposal and the regulation is not strict for the small-scale industries. This is the important factor that, in the present situation, the waste amount is increasing and directly affecting the environment (Dimou et al., 2015). There is an urgent need for wine industries to reduce their detrimental environmental effects, as indicated in ISO 14000 (Oliveira et al., 2013). A complete overview of the production of different winery wastes during different stages of the winery production system and their environmental effects are presented in Fig. 4 and S1.

Some solid organic waste like cellulose, hemicellulose, and lignin from grape marc and stalk are not looked as major pollutants but environmental problems may arise as these materials have high chemical oxidation demand during disposal (Flores et al., 2019; Spigno et al., 2007). The ecological impact of wine production drew the attention of firms and researchers on the importance of wine industry sustainability.

4.1. Effluent water

The wine industry is associated with a large amount of wastewater production. The estimation shows that the 4 m^3 of wastewater is

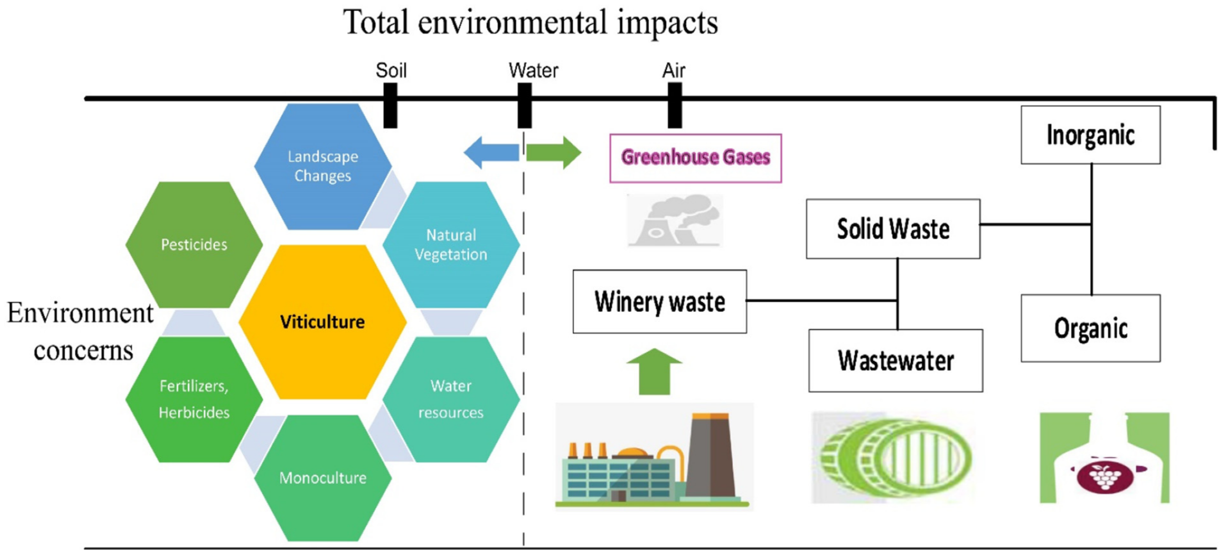

Fig. 4. Total environment impact by the winery production system.

generated per cubic meter of wine. The wastewater is produced in many winery procedures, and the major activities are like cleaning, washing, equipment, tanks, barrels, cooling and bottling as shown in Fig. S2 (Anastasiadi et al., 2009; Bolzonella et al., 2010). The management of wastewater is a difficult procedure due to its seasonal production. As the majority of the effluent is generated during the harvest period. The amount of wastewater is more vintage to the season of harvesting and juice handling (Bilal et al., 2017; Ruggieri et al., 2009).

The literature suggests that even the major wine-producing countries have issues with the management of wastewater (Fermoso et al., 2018). The activated sludge could be a better solution for proper management but the initial investment in infrastructure is a major issue for many producers. Moreover, water is directly allowed to flow in the sewage system (Ioannou et al., 2015; Lofrano and Meric, 2016).

5. Classical biorefinery vs. integrated biorefinery

The concept of biorefinery came into existence to tackle down the situation of worldwide energy calamity, and climate change attributes due to intensive industrialization. A biorefinery is an integrated, efficient, and flexible approach for the transformation of available biomass into a wide range of bio-based products by using different processes (Bilal et al., 2017; Bilal et al., 2018). The biorefinery approach is comparable to petroleum refineries. According to the international energy agency, the biorefinery is justifiable synergistic processing of biomass in different forms of energy (Tuck et al., 2012). The integrated biorefinery system could provide a great alternative to the problems of environmental concern by converting waste products in the energy and related high-value products (Ragauskas et al., 2006). The importance of biorefinery can be understood by the fact that solid and liquid waste has been successfully utilized for the biorefinery approach in the grape winery. The solid waste generated can be used for conventional biorefinery, whereas effluent can be utilized for bioconversion feedstock. The integrated biorefineries system is similar to a conventional biorefinery in that they produce a range of products to optimize production economics and the use of feedstock. The integrated biorefinery system provides the possibility to get multiple bio-based products including biochemical and energy products such as electricity, heat or biofuels. Process integration can significantly influence the profitability and suitable product diversification can help industries to manage during low demand crisis.

The benefits can be obtained in terms of reduced transport costs and energy, consumption of surplus energy and diverse product for big marketing. This system is an emerging trend for promising alternatives to fuels and chemical production from available biomass. A sufficient and sustainable supply is not possible from the available fossil resources. The grape winery is a good source of lignocellulosic biomass as a carbon source, integrated biorefinery facilities co-production of various products, and a feasible alternative to speed up the production as well as alternative of fossil fuels.

The integrated winery could be the most promising way for the generation of new bio-based fuels and compounds. The product generated from this approach (Fig. 5) is based on renewable feedstocks, which are good for the environment and better alternative for fossil products (Cherubini, 2010). The diverse product's production from integrated biorefinery can get the benefit of the differences in biomass ingredients and their intermediates to exploit the value resulting from the biomass feedstock (Ahlgren et al., 2015). With the advances in modern technologies, biorefinery can yield a series of green energy sources with minimal waste and emissions (Fatih Demirbas, 2009).

However, for the transition from the traditional approach to a biobased economy, many additional efforts are needed. The winery biomass is a good source of lignin, carbohydrates, proteins, and fats (Ioannou et al., 2015; de Villiers et al., 2012). The development of biorefinery schemes can be utilized for the use of grape releasing by-products as raw materials for the production of new products starts to be a good-looking substitute approach. The integrated biorefinery approach (Fig. 5) in the grape winery can be considered a complete way for the creation of industry-based products from grape winery waste. It could be the best solution to replace the traditional biorefinery system. The integrated biorefinery approach can provide good chances to separate the ingredients in its simpler forms to allocate and permits the highest yield in terms of bio value. The integrated biorefinery approach during winemaking offers for the best exploitation of by-products in industrial segments not in opposition to that of wine.

6. Life-cycle assessment (LCA) and winery waste management

The wine industry often considered eco-friendly. However, the cultivation of grapes and wine production (Fig. 6) is far from nature. The winery has a large impact on socioeconomic conditions, so it becomes important to identify the environmental impact of wine production. The LCA, cradle to grave analysis, could be the best approach for assessing the environmental association from extraction to disposal (Ardente et al., 2006; Parra-Saldivar et al., 2020). LCA for biorefinery, therefore, must be performed to investigate the environmental impacts

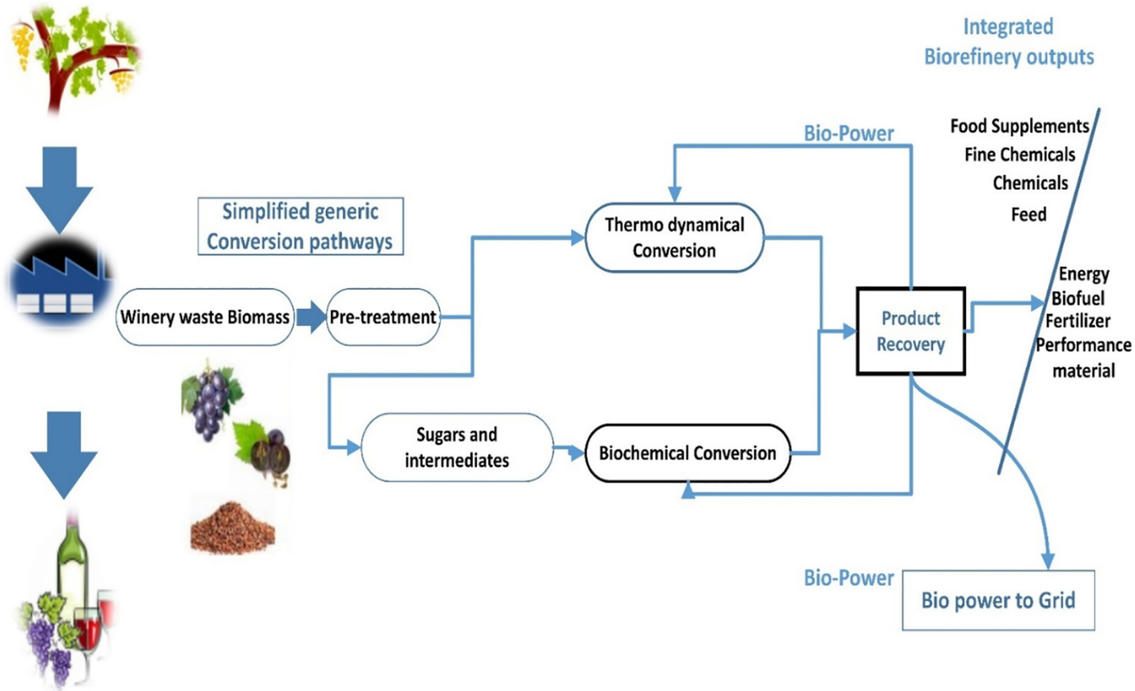

Fig. 5. Typical conversion pathways in grape waste biorefinery.

of merchandise by keeping in mind all inputs and final outputs of materials and energy flow throughout whole processes like extraction and processing of raw material, manufacturing, consumption, distribution, maintenance, and finally disposal. In general, LCA is a tool to quantify the sustainability of the process or end product (Neto et al., 2013). The number of researches were conducted for the optimization of the overall process to achieve maximum sustainability. The raw materials in the winery are just grape waste, yeast, and some chemicals, the way of using them is different. The basic steps are the same for small to giant producers, however the quality of the apparatus vary extremely. The up-to-date winery route is complicated and several steps like different thermal, clarification, filtration, stabilizing and aging processes, which is a basic part to determine the quality (Ardente et al., 2006). Hence, the inventory table is difficult to make since it varies according to the grape quality and production unit.

7. Composting: a leading biorefinery method for winery waste

The winery sector and agriculture-based industry are generating organic waste, which is increasing every year. Uncontrolled breakdown of organic winery waste can affect the environment in multiple ways. The decay of 1 metric ton of organic solid waste has ability to produce 50–110 m^3 of CO_2 and 90–140 m^3 of CH_4 into the atmosphere, therefore, management of organic winery waste is also very important. The

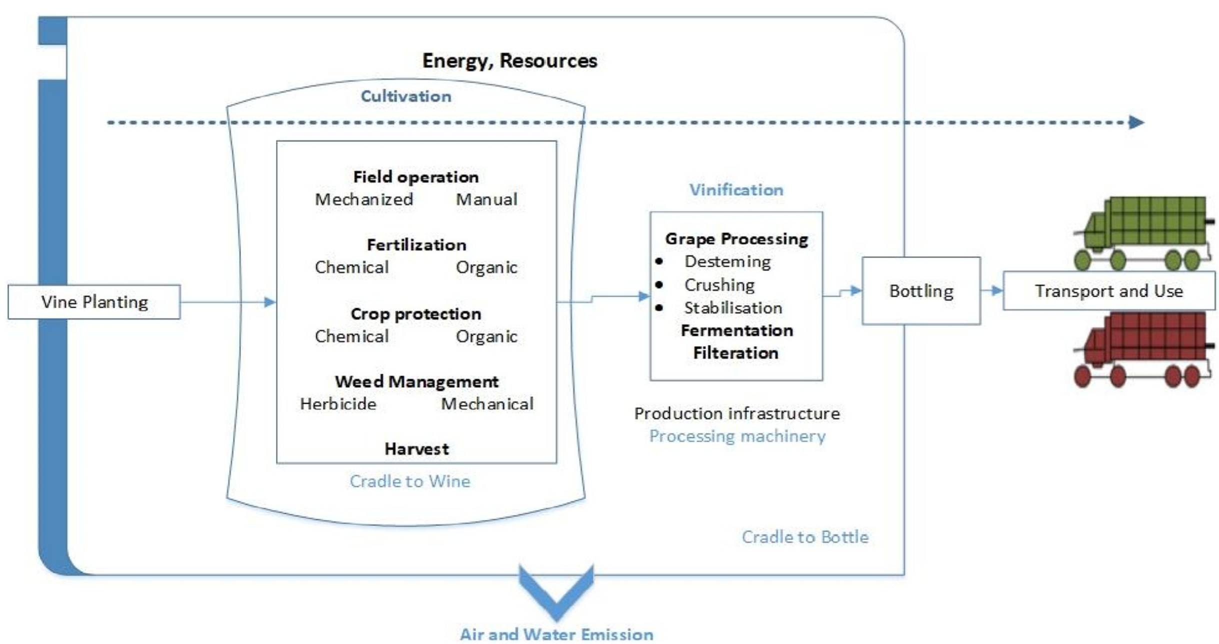

Fig. 6. Wine production model for inventory assessment.

majority of winery industries are dumping the organic waste and some are making products including compost (Paradelo et al., 2010), animal feed, and bio fertilizers (Bustamante et al., 2008b). The quality of bio fertilizer or compost depends upon the part of organic matter which can be easily available as a humus. Compost is considered as a good fertilizer because of its various organic content. The composting of winery waste has been shown a feasible method to utilize the huge amount of organic waste generated from winery (Bustamante et al., 2009; Bustamante et al., 2010; Nogales et al., 2005). The composting is good solution because of its inexpensive nature. In this process, the generated compost can be utilized for increasing organic content, nutrient levels (slow release over a long period), and microbial biomass. The seasonal availability of the raw material, however demands proper planning and investments in composting infrastructure. The areas of continuous supply of organic waste can help to achieve economic feasibility and efficiency. Further more research is required to scale up the composting process to overcome the issue of slow digestibility of winery waste. The moderate amount of vinasse can be beneficial for the composting process and optimal for production (Diaz et al., 2002).

8. Value-added energy products

Any waste (solid, liquid, or gaseous) has an innate net positive energy that can be recovered and recycled to produce bio-based products and biofuels through a cascade of closed-loop bioprocesses, allowing the transferal of a trend towards a circular and low-carbon bioeconomy. Agriculture industry wastes are gradually being used as a substrate for the production of energy.

8.1. Bio-gas

Major components of biogas are methane (CH_4) and carbon dioxide (CO_2) (Ribeiro et al., 2016). Apart from these, other gases (H_2S, NH_3, O_2, CO, N_2) are produced in smaller proportions (Ghouali et al., 2015; Ryckebosch et al., 2011). Throughout the world, scientists are evaluating different methodologies for biogas production from organic substrates. The key by-products produced in vineyards are bagasse, stems, and dregs, the anaerobic digestion of this biomass can produce biogas (Boulamanti et al., 2013; Gasol et al., 2011). Da Ros et al. (2016) assessed the reutilizing of vineyard deposits through anaerobic co-digestion with the help of activated sludge and reported that waste obtained yields of 0.40 Nm^3/kg COD-with 65% methane. El Achkar et al. (2016) described that anaerobic digestion of pomace, pulp and seeds has the potential of methane production. Co-fermentation of mixed substances provides a good feedstock for biomethane production. For example, co-fermentation of seaweed *Furcellaria* (substrate) and winemaking waste (inoculum) significantly increased biogas production output from seaweed substrate. The co-digestion of winery wastewater can also improve methane production from winery waste with swine manure (Riaño et al., 2011). Co-fermentation of white grape skins (separated from marc) with yeast extract (*Saccharomyces cerevisiae*) increased bioethanol production 15% compared to control fermentation. This approach can produce 310 l of ethanol from one ton of dry white grape skin (Mendes et al., 2013). Caramiello et al. (2013) examined biogas creation from grape marc and grape seeds through anaerobic digestion. Net methane production of 116 and 175 L CH4/kg VS (volatile solids) were obtained for grape marc and seeds, respectively. Guerini Filho et al. (2018) assessed biogas and methane production from organic by-products of wine. According to the results grape must has the greatest potential of biogas and methane production. The efficiency of anaerobic digestion (methane production) can be improved by mechanical pre-treatment (grinding) of grape marc (El Achkar et al., 2016).

Thermophilic anaerobic digestion of winery distillery wastewaters can produce biogas. The efficiency of biogas production can be improved by increasing hydraulic retention time (HRT) and the use of co-substrates. Biogas has a high percentage (76%) of methane, making it an appreciated fuel (Vlissidis and Zouboulis, 1993). Jasko et al. (2012) performed experiments about biogas production from winemaking waste-yeast biomass and wine residue containing substrate (wine lees). According to their results, due to low buffering capacity and ease of degradation, wine less is a suitable substrate for biogas production. The life-cycle assessment of anaerobic digestion process was studied against ecosystem quality, climate change, human health and resource impact indicators. It was found to be very favorable from the environmental point of view, as compared to other alternatives (Lempereur and Penavayre, 2014).

8.2. Bio-fuel

In recent years, biofuels have gained attention as a substitute for petroleum-based fuels due to environment and energy issues related to petroleum-based fuels. The term biofuel is used for any plant-based liquid fuel which can be used as a substitute for petroleum-derived fuel. Currently, biofuels obtained from grapes are classified into first-generation (foodstuff) and second-generation biofuels (non-food raw materials) depending on the source of feedstock. Bioethanol is identified as biofuel a substitute to petro-fuels and produced basically from foodstuff (first-generation bioethanol) (Bai et al., 2008). Due to the increasing demand for food and reduction in the world reserves of energy, the finding of substitute materials and energy bases is the dire need of time. According to Mendes et al. (2013), residual sugars in grape skins can be a good source for the manufacturing of second-generation (2G), (bioethanol derived from non-food raw materials) bioethanol. Practically 11 kg of oleanolic acid and 250 L can be formed from one ton of grape skins. In comparison to first-generation bioethanol, 2G bioethanol has a greater possibility for maintainable products because it doesn't compete with food production (Naik et al., 2010). Biodiesel production from grape seed founds a monetary substitute for the valuation of by-products got from the wine industry (Ramos et al., 2009). After mechanical separation, the seeds are crushed to produce polyunsaturated oils. The obtained oil can be used directly in internal combustion engines (May cause fouling with time), distributing the triglyceride molecule may cause cleaner burns of single-stranded methyl or ethyl esters (Keiluweit et al., 2010). The oil obtained from seeds is preferably used in engines to reduce friction between different parts and increase the engine life by reducing internal heating and wear. Fernández et al. (2010) used different techniques to produce biodiesel from grape seed. According to oil extraction and stability point, soxhlet extraction was reported to be the best method. In comparison, ethyl esters were better than methyl ester in terms of oil cold flow features. In short final product of trans-esterification can be used for the production of conventional biodiesel. Low-temperature pyrolysis can change dried grapes into carbon products. The gross heat produced from the combustion of grape charcoal briquettes was 90% as compared to commercial briquette, while the dried press-cakes contained almost 65%.

8.3. Miscellaneous products and platform chemicals

In the last few years, increasing research trends in the field of product revalorizing has reported many valuable by-products of the wine industry. Now a day's grapeseed oil and wine pomace (grape pomace) is being used as a source of many products. Grapeseed is being used for multiple purposes such as for heating and cooking due to its high smoke point (216 °C), clean and light taste, respectively. Grapeseed oil is considered to have enough concentration of antioxidants and substances which can lower cholesterol levels. High linoleic (76%) product obtained from grape seed oil is the only food recognized to increase HDL (good cholesterol) and lower LDL (bad cholesterol). The lower level of HDL is also a risk factor for ineffectiveness. Recently there is an increase in the use of grapeseed oil in the cosmetic industry due to its regenerative and restructuring qualities. It is very light so it is captivated by the skin and will not leave any oil residue. Its antioxidant characteristics are essential for minimizing skin aging (Arvanitoyannis et al., 2006b). Tiwari et al. (2009) reported that the use of biomolecules present in the grape seed could hinder foodborne pathogen development in cooked beef. Winery waste is a good source of natural antioxidants. Treated wine waste can be consumed as a soil amendment to reduce the toxic effects of heavy metals as well as for fertilizer and pullulan production.

The winemaking industry produces big quantities of wine pomace (grape pomace). Owing to the occurrence of large contents of nutrients and bioactive compounds in pomace, it has gained the attention of food scientists. In the past, it has been used as a source of wine alcohol, tocopherol, and tocotrienol recovery (Gornas et al., 2015) or for improvement of sensorial characteristics of beverages (Makri et al., 2017). However, according to recent findings, pomace is also a decent base of bioactive compounds (Details are given in Table 4), such as phenols, tartaric acid, and the manufacturing of flours. The greatest typical purposes of pomace are their usage as antioxidants, antimicrobial, and fortifying coloring (Garcia-Lomillo and Gonzalez-SanJose, 2017). These products have mostly been practiced for the preparation of meat and fish products and to a slighter level, cereal products. Additionally, other studies have shown that winery waste represents an innovative feed additive. The feed additive (Having bioactive compounds) decreased oxidative stress in different tissues and blood of broilers (Makri et al., 2017).

Recently, due to the increasing demand for natural food additives to ensure food safety has attracted the attention of the researcher to identify new natural preservatives. In this scenario, revalorization of the winery by-products based on the recovery of bioactive compounds has also gained attention (Teixeira et al., 2014a). Due to the development of maintainable green substitute skills for the extraction of bioactive composites from winery wastes and by-products (Barba et al., 2016), many phenolic compounds are reported in last years. A complete up to date list of phenolic compounds extracted from the winery by-products is presented in Table 4. Every day there is an increase in demand for natural organic food products. Due to this reason, the selection of raw agriculture resources for recognizing novel natural stabilizers is in the limelight (Moure et al., 2001).

9. Constructive remedies and gap remark for future winery perspectives

The increasing number of wineries are directly responsible for a huge amount of waste generation. The winery waste is different from other agriculture wastes because it has limited use as an animal feed and compost fertilizer. Since winery waste is organic, it can be used for the generation of energy through the integrated use of microbial and industrial biotechnology techniques with engineering techniques. Several studies have demonstrated that such an energy generation process can cause an environmental issue. Therefore, it is suggested further studies are required to understand sustainable biodegradation of such waste using microbes. The alternative to winery waste disposable different useful products such as lactic acid, biocontrol agents and biosurfactants can also be produced. Further, research in this direction can be helpful in generating more potential products from grape vinasse. Although several reports are available demonstrating biofuels production from winery waste, reports on commercial products or

Table 4
Phenolic compounds/platform chemicals from by-products of winery waste.

Chemical	By-product	References
Phenylethanoids		
Hydroxytyrosol	Seed	(Casazza et al., 2010)
Hydroxybenzoic acid		
p-hydroxybenzoic acid	Seed	(Casazza et al., 2010) (Cotea et al., 2018; Pintać et al., 2019)
Gallic acid	Red grape must, seed, pomace	(Casazza et al., 2010; Cotea et al., 2018; Obreque-Slier et al., 2010)
Protocatechuic acid	Seed	(Casazza et al., 2010; Cotea et al., 2018; Pintać et al., 2019)
Vanillic acid	Seed	(Cotea et al., 2018; Pintać et al., 2019)
Syringic acid	Seed	(Casazza et al., 2010; Cotea et al., 2018; Pintać et al., 2019)
O-hydroxybenzoic acid (salicylic acid)	Seed	(Cotea et al., 2018)
Ellagic acid	Seed	(Cotea et al., 2018; Pintać et al., 2019)
Hydroxycinnamic acids		
Caffeic acid	Red grape must, seed, pomace	(Kadouh et al., 2016; Rebello et al., 2013)
p-coumaric acid	Red grape must, seed, pomace	(Rebello et al., 2013)
Ferulic acid	Red grape must, seed	(Pintać et al., 2019; Rózek et al., 2007)
Trans-caffeoyltartaric, trans-coumaroyltartaric acid	Red grape must	(Boido et al., 2003; Castillo-Muñoz et al., 2009; Dresch et al., 2014)
Hydroxycinnamoyl-tartaric, Hydroxycinnamic acid derivative of caftaric acid	Seed	(Rebello et al., 2013)
Flavonols		
Kaempferol, kaempferol-3-O-glucoside	Pomace	(Fernandez et al., 2015; Teixeira et al., 2018)
Quercetin	Red grape must, seed, pomace	(Agustin-Salazar et al., 2014; Casazza et al., 2016)
3-O-glucuronide	Pomace, seed	(Chen et al., 2018)
Myricetin	Pomace, seed	(Kadouh et al., 2016; Tiwari et al., 2009)
Anthocyanins		
Anthocyanidin 3,5-diglucoside	Seed	(Rebello et al., 2013)
Malvidin-3-O-glucoside	Pomace, seed	(Chen et al., 2018; Guchu et al., 2015)
Malvidin 3,5-diglucoside	Seed	(Boido et al., 2003; Monagas et al., 2006)
Malvidin-3-acetylglucoside	Seed, pomace	(Boido et al., 2003)
Malvidin chloride	Pomace	(Kadouh et al., 2016)
Peonidin-3-O-glucoside	Seed	(Dresch et al., 2014)
Delphinidin chloride	Pomace	(Kadouh et al., 2016)
Delphinidin-3-O-glucoside	Seed	(Boido et al., 2003; Llobera and Cañellas, 2007)
Cyanidin chloride	Pomace	(Guerini Filho et al., 2018)
Cyanidin-3-O-glucoside	Seed	(Chen et al., 2018)
Petunidin-3-O-glucoside	Seed	(Boido et al., 2003; Chen et al., 2018)
Petunidin-3-O-acetylglucoside	Seed	(Boido et al., 2003)
Malvidin-3-O-coumarylglucoside	Seed	(Boido et al., 2003; Teixeira et al., 2018)

patents in this regard are very few. It is likely due to the poor understanding of the microbial mechanism of metabolite productions, and funding policies for research in academia-industry across the world. In the future, a detailed study on LCA, carbon footprint, energy production, and comprehensive economic risk analysis of integrated biorefinery must be carried out. Furthermore, lack of risk analysis factors directly linked from grape biorefinery could be the possible reason for ignorance and we suggest studies specific to human health impact should be analyzed. These studies will pave the path for commercial production of biofuels from grape winery waste.

10. Conclusions and future outlook

The winery waste is a serious challenge for the environment due to improper handling and management. The efficient disposal of winery waste is a critical problem from an economic and environmental point of view. Therefore, an ideal strategy is required to address such growing problems by the expansion of the winery industry and finally waste generated from the winery. The biorefinery approaches such as pyrolysis, fermentation, gasification, anaerobic digestion (AD), incineration, refuse-derived fuel (RDF), and plasma arc gasification have emerged with hope for proper conversion of waste to energy concept. However, the biorefinery has a limitation to produce a specific fuel depending on the availability of organic waste material. The winery waste has great potential and economic value. The winery waste has attracted the attention of researchers because of its high bioactive compounds and value added energy products. Therefore, the technologies could be brought under one umbrella as an integrated biorefinery approach for utilization of mixed and multiple winery waste to generate various products in the form of food, feed, fuel, and clean energy along with value-added chemical compounds.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137315.

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