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Sustainable green processing of grape pomace for the production of value-added products: An overview

Talat Ilyas [a,1], Pankaj Chowdhary [a,1], Deepshi Chaurasia [a], Edgard Gnansounou [b], Ashok Pandey [c,*], Preeti Chaturvedi [a,*]

[a] Aquatic Toxicology Laboratory, Environmental Toxicology Group, CSIR-Indian Institute of Toxicology Research, Vishvigyan Bhawan, 31, Mahatma Gandhi Marg, Lucknow 226 001, Uttar Pradesh, India
[b] Bioenergy and energy planning, IIC, ENAC, École polytechnique fédérale de Lausanne (EPFL) Station 18, CH-1015, Lausanne, Switzerland
[c] Centre for Innovation and Translational Research, CSIR-Indian Institute of Toxicology Research, Vishvigyan Bhawan, 31, Mahatma Gandhi Marg, Lucknow 226 001, Uttar Pradesh, India

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A B S T R A C T

In recent years, the recovery of valuable compounds from food waste like grape pomace is an emerging issue in the food sector. Grape pomace or marc can be considered as an important solid waste that is produced from the wine industries after the pressing and fermentation process. The waste produced from the wine industry causes pollution, difficulties in disposal/management, and also economic loss. Grape pomace consists of approximately 10%–30% of the crushed grape mass and other value-added products like unfermented sugars, polyphenols, pigments, alcohol, and tannins, etc. The recovery of these compounds by the most suitable and eco-friendly manner extraction techniques and able to maximize yield without compromising the stability/quality of the product is a challenging task. Grape pomace has greater potential values, there are technologies still to be developed and adopted in the winery and other associated industries. Since grape pomace is a natural plant product, it is rich in lignocellulosic compounds and could be used as a promising feedstock for the production of renewable energy. This review gives a brief overview of the extraction techniques like, Solid–Liquid Extraction, Supercritical Fluid Extraction, Accelerated Solvent Extraction, Microwave-Assisted Extraction, Enzyme Assisted Extraction, etc. Besides, the extraction of value-added products from the grape pomace and the biochemical and thermo-chemical management for recovery of energy, production of alcohol, fuel, and beverage, other novel products, and various applications such as environmental remediation and bio-surfactants are described briefly.

Contents

Abbreviations: GP, Grape pomace; SLE, Solid—Liquid Extraction; SFE, Supercritical fluid extraction; (SC-CO_2), Supercritical carbon dioxide; ASE, Accelerated Solvent Extraction; PEF, Pulsed electric fields extraction technique; PLE, Pressurized liquid extraction; UAE, Ultrasound-assisted extraction; MAE, Microwave-assisted extraction; EAE, Enzyme-assisted extraction; HVED, High voltage electric discharge; HPP, High-pressure processing; DES, Deep eutectic solvents; PUFA, Polyunsaturated fatty acids; PL, Pectin lyase; PG, Polygalacturonase; PME, Pectin methylesterase; GPSE, Grape seed phenolic extracts; PWGPE, Purified white grape pomace extract; GAE, Gallic acid equivalents; MPa, Megapascal Pressure Unit; RSD, Reflex sympathetic dystrophy syndrome; MAPK, Mitogen-activated protein kinase; IL, Interleukin; TNF, Interferon Tumor necrosis factor

* Corresponding authors.
E-mail addresses: ashok.pandey1@iitr.res.in (A. Pandey), preetichaturvedi@iitr.res.in (P. Chaturvedi).

1 Contributed equally.

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1. Introduction

The production of wine is a significant part of the agriculture and beverage industries. Recent evidence stated that 292 million hectoliters of wine were produced worldwide in the year 2018 (OIV, the International Organization of Vine and Win, 2013). On average, in every season, around 100 tons of grapes are being crushed by the winery industry for wine production. The making of wine is an opportune task, which occurs in the southern hemisphere from January to April, and in the northern hemisphere, it occurs from August to October. As compared to sparkling and fortified genres of wine, the production of wine is still achieving the largest part of the market. According to the annual production report, with approximately 77.8 million tons of production, the grape is one of the most widely evolved fruit crops in the world (OIV, the International Organization of Vine and Win, 2013). The overall area covered by vines in the year 2018 was considered to be slightly higher than in 2017, which increases up to 7.4 mha (millions of hectares; OIV, 2019). In 2017, the amount of total land covered by the vine (7.6 mha) has been stabilized. About 50 million tons of grapes are produced every year, and out of which about 75% is spent on the production of wine (Zhu et al., 2015; Beres et al., 2017).

A huge amount of waste is generated by the wine industries, which consist of stalks, grape marc, wastewater sludge, and yeast lees. The discarding or disposal of winery waste could have several toxic environmental impacts. During the preparation of the must, whole bunches of grapes are pressed for the generation of grape marc. According to Mendes et al. (2014) and Garcia-Lomillo and Gonzalez (2017) for each 6 L of wine, around 1 kg of pomace is generated. Traditionally, Grape pomace is being used as the conditioner for soil and feed. Grape pomace can also be used for the production of a large number of value-added components. These components consist of edible acids (tartaric, malic, and citric acids), ethanol, dietary fiber, and grape seed oil (Maier et al., 2008). Additionally, grape marc has also been admitted as an important source for polyphenols, including flavonoids, anthocyanin, proanthocyanidins, and phenolic acids (Fontana et al., 2013; Beres et al., 2017; Garcia-Lomillo and Gonzalez, 2017; Del Pino-García et al., 2017).

After the production of wine, the process of valorization targets the byproduct recovery for the value-added products. The major focus is to use agricultural industrial residues as the raw material for the industries. This will result in a reduction of the harmful effects caused by industrial residues on the environment. Major concerns are shown for the extraction of different useful components like phenolic compounds and functional foods from the grape byproducts. An example of such a case is that, in the course of extracting grape seed oil, both phenolic extracts and antioxidant dietary fibers are recovered from the grape pomace, thus making this overall process more sustainable (Environmental Protection Agency, 2015).

The properties such as antifungal, antimicrobial, anti-inflammatory, anti-cancer, and cardioprotective effects have been shown by the polyphenols extracted from the grape pomace (Ky et al., 2014). In this topic, the valorization of winery byproducts provides other possibilities to reduce the adverse effects caused on the environment after the wine production and to encourage the commercialization of oil, and dietary fibers (noodles, biscuits, whole grain bread, and steamed bread) from grape pomace and bioactive components rich extracts. With this perspective, the methods are being modified for the recovery of bioactive components from grape pomace to encourage a quicker and "greener" technology. Extraction techniques such as sub/supercritical, enzyme-assisted, and ultrasound are being considered for extracting the value-added products or components from the fruit residues (Alexandre et al., 2018).

The main objectives of this review manuscript are to analyze the idea that can be used at the industrial scale to utilize the grape pomace and built up the new concepts of bio-refinery, i.e. to use the waste material from wine industries as the source of fuel, energy, chemicals, heat, and other miscellaneous applications.

2. Sources of grape winery waste

Waste from wine industries can be characterized into solid and liquid waste. The winery industry waste (solid) generation is due to the collection and processing of grapes whereas liquid waste is produced during the winemaking process. A huge amount of waste is generated during the cultivation of the vine itself and in the production of wine in cellars. There are certain side products also generated which include stem, seeds, pomace, yeast, bacteria lees, organic acids, CO_2, prunings, and water. The materials obtained are used for the generation of products like fertilizers, animal feeds, etc. (Rondeau et al., 2013). The solid waste consists of grape stalks, grape seeds, and grape pomace, which vary in texture and chemical compositions. Broome and Warner (2008) stated that the waste source obtained from winery industries composed of approximately 45% grape pomace, 7.5% grape stalks, 6% grape seeds, and many other wastes. With the production of approximately 5 tons per hectare per year, grape stalks are the major byproduct of the vineyard (Barrantes Leiva et al., 2014). They are of agronomical value and contain a generous amount of cellulose, lignin, sodium (Na), and potassium (K). Due to low organic matter content (∼2%–3%), grape stalks are used for composting since they are effective for soils (Nerantzis and Tataridis, 2006).

3. Physico-chemical characteristics of grape pomace

Grape pomace is a highly variable product. It contains erratic proportions of stems, seeds, pulps, and skins. The type of fruit maturity, grape cultivars, and the production process affect the composition of the pomace. However, despite this unevenness, grape pomace is a feed of moderate to low nutritional value. In the studies conducted by González-Vázquez et al. (2017), Mäkelä et al. (2017), Botelho et al. (2018), Khiari and Jeguirim (2018a,b), Gowman et al. (2019), the most abundant element found in the grape pomace was carbon, 54.0%, followed by oxygen 37.85% and hydrogen at 6.08%. The amount of nitrogen was found to be 1.99%, and traces of sulfur were found at 0.08%. The protein content found is about 14% and the fiber content is generally high ranging from 26%–70% with exceptional levels of lignin ranging about 18%–55%. Grape pomace contains 4%–11% lipids because of the presence of the oil-rich seeds. The sugar content can vary from 4%–9% in red wine pomace to 28%–31% in white wine pomace (Heuze and Tran, 2020).

4. Extraction techniques

Grape pomace and grape seeds are been used for the extraction of different by-products such as linoleic acids and omega-6 fatty acids with about 6% phenolic content. Grape pomace is also being used as an additional agent with the feed due to its rich fiber content. Extraction is one of the important steps in the identification, isolation, and recovery of components from the winery waste produced since there are no standard extraction methods available (Table 1). The methods of extraction are divided into two categories: conventional or traditional and nonconventional (Fig. 1).

The traditional methods that are being used for a very long period, include soxhlet extraction, maceration, and reflux extraction, etc. In these methods, a large amount of solvent is required and hence, these are not advantageous for commercial purposes (Wang and Weller, 2006). Other than this, boiling is being required in these methods, which leads to the loss of products like polyphenols (Fontana et al., 2013). Because of certain drawbacks, there was a need for the development of new methods that are considered non-conventional extraction methods. These methods include techniques such as supercritical extraction, ultrasound-assisted extraction, accelerated solvent extraction, pressurized fluid extraction, and microwave-assisted extraction. These techniques require a short span of extraction time of about 1–60 min and less amount of solvent i.e., about 50 ml as compared to conventional methods which require about 100–200 ml of solvent and 500–700 min for the extraction process (Tatke and Rajan, 2014).

Solid–liquid or Soxhlet extraction is the traditional technique that has been used for many decades. Since the traditional methods are more time taking and also require a large number of solvents, the techniques are being primarily focused on shortening the time of extraction, reducing of consumption of organic solvents, and increasing sustainability while improving the production of valuable components. The following techniques are majorly being used for the extraction of value-added compounds from the grape pomace (see Table 2).

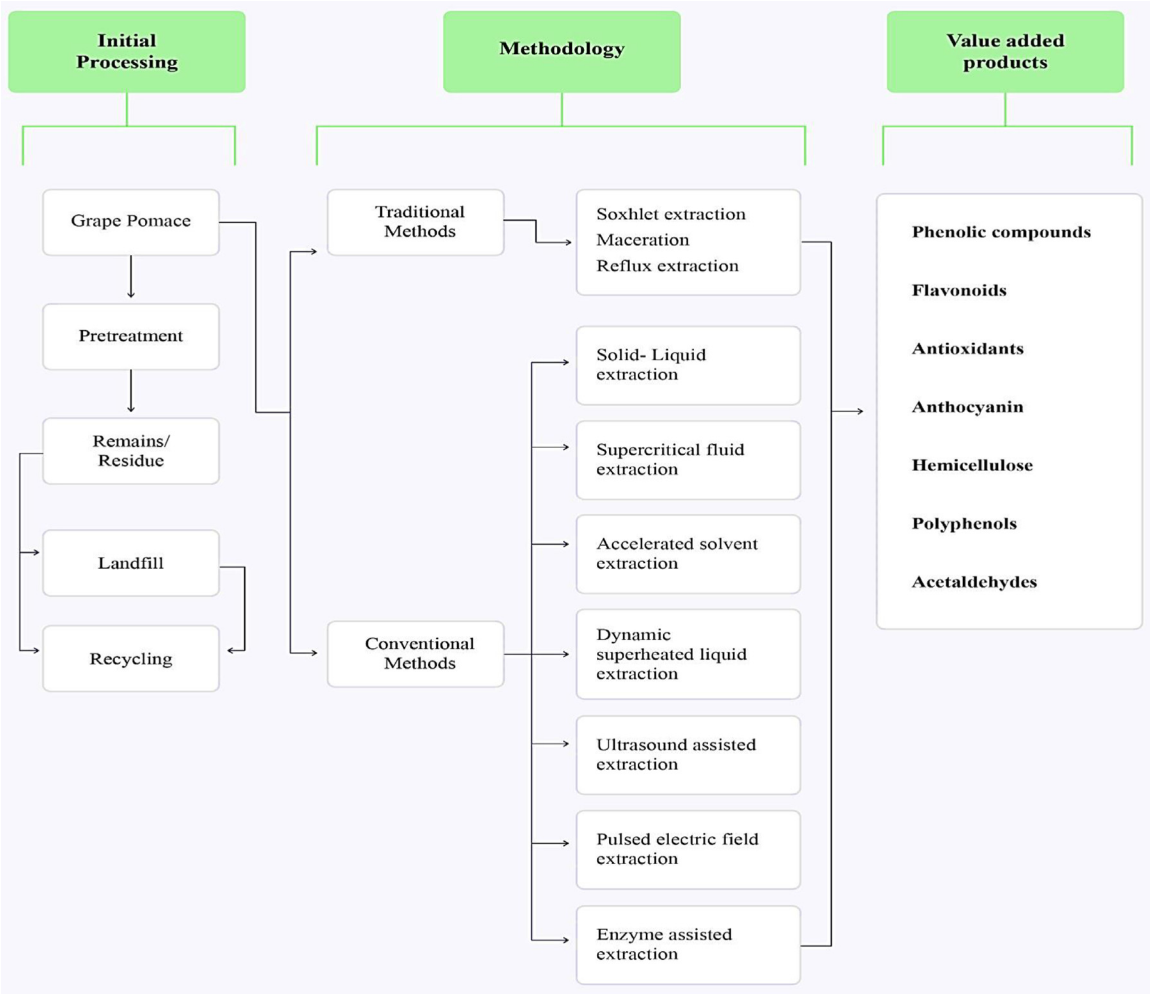

Fig. 1. An overview of grape pomace processing by different methodologies and derived value added by-products.

4.1. Solid–Liquid Extraction (SLE)

Solid–Liquid extraction can be explained as a mass transport phenomenon in which the analytes present in a solid matrix are migrated into a solvent phase which is in contact with the matrix. The extraction of diverse components present in fruits, which includes flavonoids, is commonly done by the solvent extraction method. The extraction of phenolic components comprises drying or lyophilization of fruits, grinding, or drenching (soaking) the fresh fruits with the respective (subsequent) solvent (Corrales et al., 2009). The mass transport phenomena can be enhanced by changing the concentration gradients and diffusion coefficients, thus improving the efficiency of the extraction. The efficiency of the extraction can be affected by factors such as temperature, particle size, types of solvent being used, extraction time, and the matrix of the interfering substance (Ignat et al., 2011). Solvent type, time, and temperature are the major factor that affects the efficiency and purity of the process as well as the recovered product. Polyphenols, because of their polar nature, are easily miscible in polar protic media i.e., HCl solutions. The phenolic fractions could be easily obtained by varying the concentrations of alcohol in the mixtures with different concentrations of low-polar solvents such as ethyl acetate (Galanakis, 2012). In a study conducted by Posadino et al. (2018), solid–liquid extraction was used for the extraction of polyphenolic antioxidants from the grape marc (Cagnulari), which was used for the production of enriched foods. In another study, recovery of polyphenols from red and white pomace was carried out using SLE. The extract obtained was used for knowing their effect on the cell differentiation on MSCs from bone marrow (Torre et al., 2020a,b). The successful application of SLE has been carried out for the extraction of various phenolic compounds from grapes. Examples of such are the extraction of trans-resveratrol from grapes and proanthocyanidins and catechins from grape seeds.

Table 1
Different processing techniques, sources, yield (%), and products.

S. No.	Techniques/approaches	Sources	Recovery yield (%)	Products	References
1.	Enzyme-assisted extraction	grape pomace	–	phenolic compounds	Cascaes Teles et al. (2020)
2.	Microwave-assisted extraction	grape pomace	–	Phenolic compounds	Drevelegka and Goula (2020)
3.	Ultrasound-assisted extraction	grape pomace	–	Phenolic compounds	Drevelegka and Goula (2020)
4.	Ultrasonication	Grape pomace	–	Anthocyanins	Zhao et al. (2019)
5.	Solid–liquid extraction	Grape marc	–	Antioxidants	Posadino et al. (2018)
6.	Ultrasound treatment	Grape pomace	80.1% cellulose	Cellulose nanocrystals	Coelho et al. (2018)
7.	Ultrasonication	Cabernet GP	–	Polyphenols	Nayak et al. (2018)
8.	Pressurized liquid extraction	Red GP	–	Oils, Polyphenols	Jin et al. (2018)
9.	Microwave acid digestion	Vine-shoots	–	Antioxidant	Spigno et al. (2017)
10.	Supercritical CO_2 extraction	Red GP	–	Polyphenols	Gonzalo et al. (2016), Martínez et al. (2016)
11.	Solid–Liquid extraction	Vine-shoot	–	Anthocyanins	Sánchez-Gómez et al. (2016)
12.	Ultrasound assisted extraction	Red GP	–	Polyphenols	Makris (2016)
13.	Supercritical CO_2 extraction	grape seed	–	oil	Jokić et al. (2016)
14.	Ultrasound assisted extraction	Grape by-products	Anthocyanin content (7%) Oils (>90%)	Polyphenols and Anthocyanin	Trasanidou et al. (2016)
15.	Ultrasound assisted extraction	Grape pomace	–	Hemicellulose	Minjares-Fuentes et al. (2016)
16.	Pulsed electric field	Fermented grape pomace	–	Anthocyanins Polyphenols	Barba et al. (2015)
17.	US-assisted extraction	Red grape pomace	–	Polyphenols, Antoxidants	Gonzalez-Centeno et al. (2015)
18.	SFE-assisted extraction	Grape pomace	–	Polyphenols, Monomeric flavan-3-ols Oligomeric flavan-3-ols Polymeric flavan-3-ols	Da Porto et al. (2014)
19.	Solid–liquid extraction	Vine shoots	–	Phenolic compounds	Rajha et al. (2014a,b)

(*continued on next page*)

Table 1 (*continued*).

S. No.	Techniques/approaches	Sources	Recovery yield (%)	Products	References
20.	Pulsed electric field	Fermented grape pomace	–	Anthocyanins Polyphenols	Brianceau et al. (2014)
21.	High Voltage Electric Discharge-Assisted	Vine shoots	–	Polyphenols, Kaempferol, Epicatechin	Rajha et al. (2014a,b)
22.	US-assisted extraction	Red grape pomace	–	Polyphenols	Gonzalez-Centeno et al. (2014)
23..	Supercritical fluid extraction	Stem, skin and seeds	–	Anthocyanins, catechins, glycosides of flavonols	Faıas-Campomanes et al. (2013)
24.	SFE-assisted extraction	Red grape pomace	–	Gallic acid, protocatechuic acid, vanillic acid, p-hydroxybenzoic acid, syringic acid, p-coumaric acid, quercetin	Faıas-Campomanes et al. (2013)
25.	Ultrasound Assisted Extraction	Grape fruit	–	Flavonoids	Carrera et al. (2012)
26..	Supercritical Fluid Extraction	Wine grapes seeds	–	Phenolic compounds	Prado et al. (2012)
27.	Supercritical fluid extraction		–	Polyphenols	Sairam et al. (2012)
28.	Pulsed electric field	Grape seeds	–	Polyphenols	Boussetta et al. (2012a)
29.	High Voltage Electric Discharge-Assisted	Unfermented red grape pomace	–	Polyphenols	Boussetta et al. (2012b)
30.	US-assisted extraction	Vine shoots	–	Polyphenols	Delgado-Torre et al. (2012)
31.	Pressurized solvent	Grape pomace	Total anthocyanin content (50%)	Flavonoids	Srinivas et al. (2011)
32.	Microwave	Grape skin	Total anthocyanins (118%)	Flavonoids	Liazid et al. (2011)
33.	Microwave	Grape seeds	Total phenolic content (13.5%)	Phenolic compounds	Li et al. (2011)
34.	US-assisted extraction	Dried Grape skins	–	Anthocyanins	Ghafoor et al. (2011)
35.	Pressurized solvent	Red grape pomace	Total anthocyanin content (45%)	Flavonoids	Monrad et al. (2010)
36.	Supercritical fluid extraction	Grape seeds	Seed oil (11.5%)	Essential oils	Passos et al. (2010)
37.	SFE-assisted extraction	White grape pomace	–	Resveratrol	Casas et al. (2010)
38.	Pulsed electric fields	Grape skin	Total polyphenol content (20%)	Phenolic compounds	Boussetta et al. (2009)
39.	High Voltage Electric Discharge-Assisted	Unfermented red grape pomace	–	Polyphenols	Boussetta et al. (2009a)
40.	High Voltage Electric Discharge-Assisted	White grape skins	–	Polyphenols	Boussetta et al. (2009a)

(*continued on next page*)

Table 1 (*continued*).

S. No.	Techniques/approaches	Sources	Recovery yield (%)	Products	References
41.	Pulsed electric fields	Grape by-products	Total anthocyanin content (20%)	Flavonoids	Corrales et al. (2008a,b)
42.	SFE-assisted extraction	grape skins extract	–	Anthocyanins	Bleve et al. (2008)
43.	Ultrasound assisted extraction	Grape by-products	Anthocyanin content (7%) Oils (>90%)	Phenolic Compounds	Corrales et al. (2008a,b)
44.	Pulsed electric field	Red grape skin	Total anthocyanin content (45%)	Anthocyanins	Corrales et al. (2008a,b)
45.	Supercritical fluid extraction	Grapefruit seeds	Limonoids (0.6%) Naringin (0.2%)	Flavanones	Yu et al. (2007)
46.	Pressurized solvent	Red grape pomace	Total anthocyanin content (45%)	Flavonoids	Nawaz et al. (2006)
47.	Pressurized liquid extraction	Grape by-products	–	Polyphenols and Anthocyanin	Ju and Howard (2003)
48.	Supercritical fluid extraction	Grape skins	Glycosides (100%)	Aroma compounds	Palma et al. (2002)
49.	Supercritical CO_2 extraction	grape skin	–	Resveratrol	Marti et al. (2001)
50.	Supercritical fluid extraction	Grape seeds	Total phenolic content (-)	Phenolic compounds	Murga et al. (2000)

Table 2
Advantages and disadvantages of conventional and modern extraction techniques.

Extraction methods	Advantages	Disadvantages
Pulsed Electric Field	- Requires low energy - Processing cost is low - High selectivity, specifically for anthocyanins	- Investment cost is high - Adaptability of apparatuses with different raw materials is poor
Superficial Fluid Extraction	-Extraction rate is fast - System is automated - Filtration is not required - Possibility of reusing CO_2 - Toxic solvents are not used - Possibility of tuning the polarity of $scCO_2$ - Thermolabile compounds can be extracted at lower temperature	- Cost of equipment is high - Requirement of elevated temperature - Risk of losing volatile compounds - Optimization of many parameters
Ultrasound Assisted Extraction	- Extraction efficiency is high - Selective extraction can be done - Rate of extraction is fast - Cost of equipment is low - Mixing efficiency is high - Operating temperature is low - Effective for thermolabile compounds - Less amount of solvent and energy used	- Filtration is required - Lack of uniformity may occur during distribution of ultrasound energy - Potential change could be present - More solvent is required
Microwave Assisted Extraction	- Faster extraction - Less consumption of solvent - Extraction yield is high - Reproducibility is good - Lower risks - Extraction time short (3–30 min)	-Equipment cost is high - requires filtration step - Poor efficiency for volatile compounds - Condition for solvent that it must absorb microwave energy
HVED	- Energy requirement is less - Extraction efficiency is high	- Degradation of extraction compounds - Lifetime of electrodes is limited - Selectivity is poor
DES	- Toxicity is less - Biodegradable - Price is less - Possibility to tune with viscosity, polarity, and density - Extraction yield is more	- Filtration step is required - Viscosity or high density of mixture

4.2. Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is a very novel method for the extraction of value-added products. It can be considered as an environment-friendly technology, which is the most employed technique and offers various advantages over classical extraction methods, by using compressed fluids. It is a green technology that allows the extraction process by limiting the thermal degradation at low temperatures and abstains from the toxic harmful solvents. A supercritical fluid can be defined as the substance above its critical pressure and temperature. It consists of good solvating power, marginal surface tension, low viscosity, and high diffusivity (Wells, 2003). The main advantages of SFE are shorter times of extraction and less usage of organic solvents with a risk of storage. Also, it can be used for the volatility of liquid/solid components recovery (Ameer et al., 2017; Santos et al., 2017). The extraction process consists of two steps. Firstly, to solubilize the existing components present in the matrix, the solvent flows through the packed bed, and in the second one, the solubilized compounds are carried to the extractor by the solvent, and the solvent-free extract is obtained by the increase in temperature and/or by a reduction in pressure (Silva et al., 2016).

Supercritical fluid extraction is distinguished for utilizing supercritical fluids, which exhibit gas-like properties (low viscosity and high diffusivity) and liquid-like properties (negligible surface tension) above their critical point (Bubalo et al., 2018). The most commonly used solvent in SFE is Supercritical carbon dioxide ($SC\text{-}CO_2$). In CO_2, because of its non-polar character, non-polar and medium polar components like waxes, oils, and fats can be dissolved (De Zordi et al., 2017;

Silva et al., 2017; Al Bulushi et al., 2018). It is non-toxic, inert, has relatively less pressure, and allows extraction at a lesser temperature. This fluid can also replace organic solvents such as heptane and hexane (Al-Hamimi et al., 2016). The extracts which are obtained by supercritical fluid extraction are of superior quality (Pereira et al., 2013). This technique targets the analytes from solid matrices. Supercritical fluid extraction allows a rapid mass transfer in the supercritical phase due to certain characteristics. It advances the efficiency to perforate the pores in the sample matrix, accomplishing a fast and efficient extraction. For improvement in the efficiency of extraction, modification of the selectivity of the main solvent and co-solvents can be done. Some authors determined that co-solvents can play the main influential factor in the supercritical fluid extraction technique (Salazar et al., 2018).

4.3. Accelerated Solvent Extraction (ASE)

Pressurized fluid extraction or pressurized liquid extraction is also known as ASE. It is one of the most used extraction techniques for the extraction of phytochemicals such as phenolic acids (Sánchez-Camargo et al., 2016), flavonoids (Leyva-Jiménez et al., 2018), and anthocyanins (Feuereisen et al., 2017) from a large variety of vegetative sources. To enhance the extraction of organic analytes from solids by using the conventional solvents, high temperature (100–800 °C) and pressure (1500–2000 psi) have been used. The upraised temperature and pressure being used in accelerated solvent extraction affect the sample, solvent used, and the interconnection between them. The extraction of organic analytes is also enhanced by the solid samples with the desired solvent. Under increased pressure, the boiling point of the solvent increases; therefore, extraction can be conducted at higher temperatures. The samples are packed in the cell with the dispersant, and the extraction can be carried out in less time (5–20 min) with the pressure of around (5–20 MPa), temperature (40–200 °C), and a suitable solvent (Kovačević et al., 2018; De Oliveira et al., 2018; Lores et al., 2015; Otero et al., 2018). The competence of this technique was studied by extracting anthocyanins and polyphenols from blackberry pulp residues left after the industrial processing and evaluation of the effect of type of solvent and temperature was also carried out (Machado et al., 2015). It was observed that at a temperature of around 100 °C, the mixture of ethanol or water was used to recover the maximum amount of bioactive with the pressurized fluid extraction technique. Phenolic compounds were obtained from myrtle leaves at temperature up to 137 °C, with the same mixture of solvents (Díaz-de-Cerio et al., 2018).

Rockenbach et al. (2012) stated that various allocated and non-galloylated flavan-3-of compounds and condensed catechin products with acetaldehyde were extracted using a proportion of acetone and water (70:30), at 25 °C. In an earlier study by Monrad et al. (2009), reported the two alternative extraction methods by ASE for procyanidins. It was seen that a mixture of ethanol and water (50:50), with the extraction cycle at 40–140 ºC, under 6.8 MPa pressure was most appropriate for the extraction of procyanidins from red GP. In this type of extraction, the temperature of the water is increased from 200 to 350 °C, resulting in a decrease of dielectric constant to around 20–30, comparable to conventional extractions (Bodoira et al., 2017).

4.4. Ultrasound-assisted extraction (UAE)

Ultrasound-assisted extraction is one of the most commonly used extraction techniques since it is comparatively easy to operate, flexible, and requires less cost in comparison to other extraction techniques. The main operation mechanism in ultrasound-assisted extraction is the phenomena of acoustic cavitation produced by the mechanical and ultrasound mixing effects. The cavitation process involves combined or independent mechanisms between sonoporation, capillarity, erosion, fragmentation, and detexuration (Fig. 2). All these processes result in the disruption of cellular content, reduction in particle size, maximum solvent penetration, reduction in the extraction time, and increase in extraction efficiency (Pena-Pereira and Tobiszewski, 2017). Intensification of mass transfer, capillary effects, and increase in penetration of solvent into plant tissue are the possible advantages of this technique. It occurs because of the cavitational collapse, i.e. growth, formation, and compression of micro-bubbles in a liquid that is present in the raw material (Mason, 2011; Pingret et al., 2013). The physical effects of ultrasound are related to lower frequencies (20–100 kHz), while the chemical effects influence the high frequencies (200–500 kHz) (Tiwari, 2015). The bioactive compounds' biological activity is pronouncedly dependent upon the extraction conditions such as type of solvent, extraction time, and temperature (Alonso-Carrillo et al., 2017). Parameters such as viscosity, the vapor pressure of the solvent, surface tension, and solubility of the target metabolites play an essential role in the choice of the solvent. The phenomenon of acoustic cavitation can be affected by these parameters, thus, a low vapor pressure solvent is preferred in ultrasound-assisted extraction (Chemat et al., 2017). Various compounds have been extracted successfully using this technique (Al-Dhabi et al., 2017; Luo et al., 2018; Pudziuvelyte et al., 2018).

UAE was used for the extraction of anthocyanins, phenols, and antioxidants, from grape seeds utilizing rotatable designs, central composite, five levels, and three variables which were extraction time, extraction temperature, and ethanol concentration (Ghafoor et al., 2009). The reduction in the time of extraction was observed from 6 hr in the case of soxhlet extraction to 30 min by UAE for the extraction of grape seed oil (Da Porto et al., 2013). In a study by Vergara and his team, they optimized an extraction method using pressurized hot water for the recovery of antioxidants from grape pomace. Total antioxidant extraction and antioxidant activity have been enhanced by the UAE extraction technique. The results showed an increase in total antioxidant extraction and antioxidant activity by increasing the extraction temperature. The maximum yield of anthocyanin was achieved at 100 °C for tannins and 150 °C for tannin-anthocyanin adduct, whereas, decrease in polyphenol yield was observed at longer extraction times and higher temperatures (Vergara-Salinas et al., 2013).

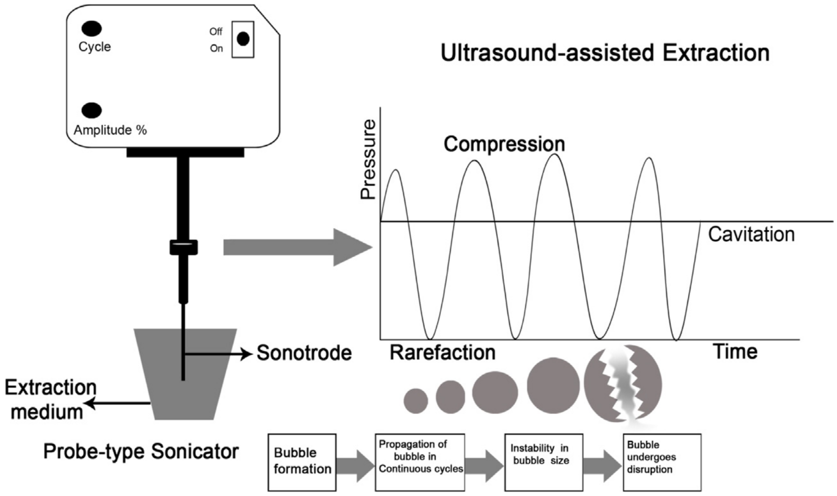

Fig. 2. Schematic flow diagram flow diagram of ultrasound-assisted extraction.

4.5. Dynamic superheated liquid extraction techniques

Dynamic superheated liquid extraction is an interesting industrial substitute for the extraction of various compounds. In this technique, superheated liquids are being used. This technique has several advantages over traditional techniques. It increases the rate of diffusion, solubility, and mass transfer of the compound whereas, decreases the surface tension by increasing the temperature above the boiling point. By these changes, the bonds between the compounds and the solvent are improved, thus enhancing the extraction. With less solvent consumption, extraction can be achieved rapidly as compared with the traditional methods. Second, the degradation and oxidation of the compounds during extraction are significantly reduced because of the absence of light and air (Luque-Rodrıguez et al., 2007). Different types of phenolic compounds have been extracted from the grape pomace using this technique.

4.6. Pulsed electric fields extraction technique

PEF treatment is a non-thermal processing technology that applies an electric field by which the sample is exposed to the short pulses of voltage with relatively less energy and medium intensity resulting in the release of the compound of interest from the cells (Bobinaite et al., 2015). This method could be used as an alternative to conventional thermal processing methods. The principle or mechanism of PFE is electroporation. i.e., the membrane's transmembrane potential increases resulting in the initiation of pores formation because of the exposure to the electric field (Yammine et al., 2018). In PEF, high voltage pulses are applied on a matter placed between two electrodes, which damage the cell wall making it easier and faster to extract cell components. Due to the potential of breaking the cells and making it easier to extract natural components, this technique took another dimension (Fig. 3). In the matter of plant tissues, the efficacy of the application of PFE is the cell membrane permeabilization that stimulates the liberation of liquid and essential components from the plant cells (Bobinaite et al., 2015; Barba et al., 2015b). In this process the mass transfer is increased without the exposure of the material to elevated-temperature conditions, hence, reducing the degradation of heat-sensitive compounds (Barba et al., 2015b). In comparison to other conventional extraction techniques, this technique requires less processing time and less consumption of energy makes it a more interesting technology for the food industries (Vorobiev and Lebovka, 2016; Frey et al., 2017). The pulsed electric fields extraction treatments could be efficiently used to enhance and improve the quality and yield of juices obtained from various fruits and vegetables: blackberries (Barba et al., 2015a), carrots (Jaeger et al., 2012), apples (Carbonell-Capella et al., 2016; Grimi et al., 2011), and grapes (Donsì et al., 2010).

According to the work conducted by Pataro et al. (2017), favorable results of the efficiency of extraction of juice and antioxidants were obtained by applying the PFE technique on blueberries and their by-products. The polyphenols present in the grape skin can be categorized as cell-wall polyphenols which are bound to polysaccharides, and non-cell-wall polyphenols are present in cell nucleus and vacuoles (Boussetta et al., 2009).PFE has been successfully used on Aglianico grapes, for increasing the phenolic content after maceration, releasing 100% polyphenols (Donsí et al., 2011). Another study by Boussetta and his team showed that by increasing the voltage from 30 to 60 kV, the yield of total phenolic content increased from 16.7% to 84.2%. The hydroethanolic solvent of grape seeds was used with PFE for preserving the structure of polyphenols and giving the highest yield of 9g/100g of GAE (Boussetta et al., 2012a,b). An increment in the total phenolic content was observed when Kyoho grape seeds were subjected to PEF underwater (Takaki et al., 2011).

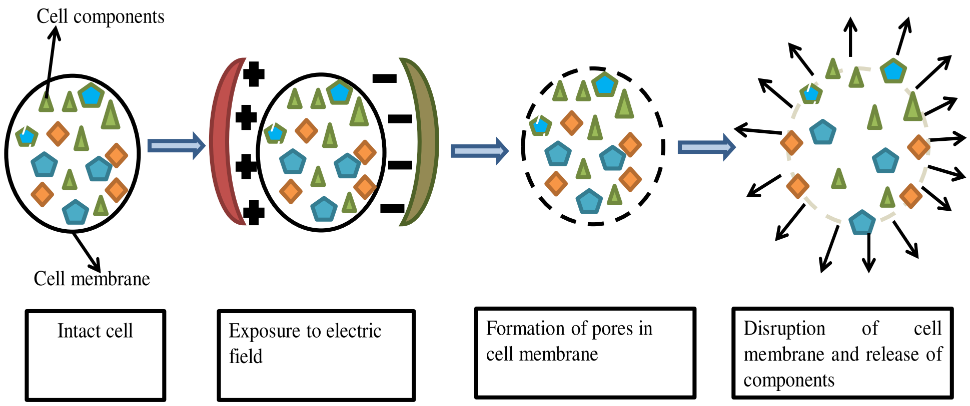

Fig. 3. Schematic flow diagram of pulsed electric fieldextraction mechanism.

4.7. Microwave-assisted extraction (MAE)

MAE is an efficient and probable technique for the procreation of phytochemicals from plants and their by-products. In this technique, the extraction of bioactive compounds is carried out in the same manner as compared to conventional techniques (Ameer et al., 2017). The MAE consists of a magnetic field and an electric field that is oscillating perpendicularly to each other, which results in the change of cell structure. The energy transfer taking place is the main process of microwave heating. The microwave energy is directly delivered to the materials by the interactions between the molecules because of which, the electromagnetic energy is converted into thermal energy (Radojkovic, 2018).

In microwave-assisted extraction, the technique is applied before the chromatographic determination of anthocyanins in the extract. Under the extraction conditions, the stability of anthocyanins extracted from grape skin was detected. The temperature range from 50 °C up to 150 °C was evaluated. To analyze the influence on the ratio of extraction of six different variables i.e. extraction temperature, extraction volume, extraction time, solvent, stirring, and microwave power, a fractional factorial experiment was designed. For the recovery of the anthocyanins from grapes, the extraction solvent is the most important variable (Fig. 4). The studies were carried on the influence of extraction time also. According to an earlier study, a method has been derived through which anthocyanins can be extracted with 40% methanol in water as the extraction solvent (5 min and 100 °C). Reproducibility and repeatability were checked, resulting in lower RSDs ($n=9$) than 7% for glucosides which was the main component, and less than 9% for acyl derivatives which was the compound found in the lowest concentrations (Liazid et al., 2011). The grape pomace produced from the processing of grapes could be used as a source of bioactive compounds. According to a study conducted by Da Rocha and Noreña (2020) the phenolic compounds were extracted from the grape pomace by using an acidic aqueous solution with 2% citric acid as solvent, along with MAE using various amounts of powers for a different interval of time. Anthocyanins and phenolic compounds can be exposed by using organic solvents with conventional extraction methods at elevated temperatures. The immersions are being used under agitation, which involves thermal refluxes in the thermal refluxes disintegrating thermolysis, and oxidation. The technologies such as UAE and MAE for the extraction of phenolic compounds are being advised to use to reduce the use of solvents, resulting in energy costs and decreased environmental impact (Zekovic et al., 2017; Sharmila et al., 2016; Barba et al., 2016). Esquivel-Hernández et al. (2017) stated that microwave-assisted extraction (MAE) techniques can be employed for the extraction of a large variety of bioactive compounds. The significant reduction in the extraction times is the main advantage of this technique. Moreover, another study conducted by Nayak et al. (2018), showed that the extraction of polyphenols with the use of microwave-assisted extraction from the *Citrus sinensis* peel was more effective as compared to the other conventional, accelerated, and ultrasound-assisted extractions. For the extraction of polyphenols from wine waste, MAE has also been used as a pretreatment, improving the efficiency by 57% of polyphenols extraction from grape pomace Álvarez et al. (2017). The MAE technique has also been used for the extraction of natural antioxidants from the shoots of the vine obtained a much greater yield than has been obtained by other conventional extractions (Moreira et al., 2018). The use of MAE was also carried out as a pre-treatment for the conventional methods of extraction for increasing the yield and decrement in the time of extraction from about 15 min to 90 s (Romero-Díez et al., 2019).

4.8. Enzyme assisted extraction (EAE)

EAE is a green extraction technique. It does not use toxic organic solvents, as compared to conventional solvent extraction. The enzyme-assisted polyphenol extraction process is used to increase the release of bioactive compounds from the matrices. The degradation of the cell wall is a compulsion during this extraction since it releases the cell components into the extraction solvent. The disruption of the cell is caused by the activity of different enzymes such as tannases, pectinases, hemicellulases, and cellulases (Puri et al., 2012). Nowadays, there are a large number of enzymes available

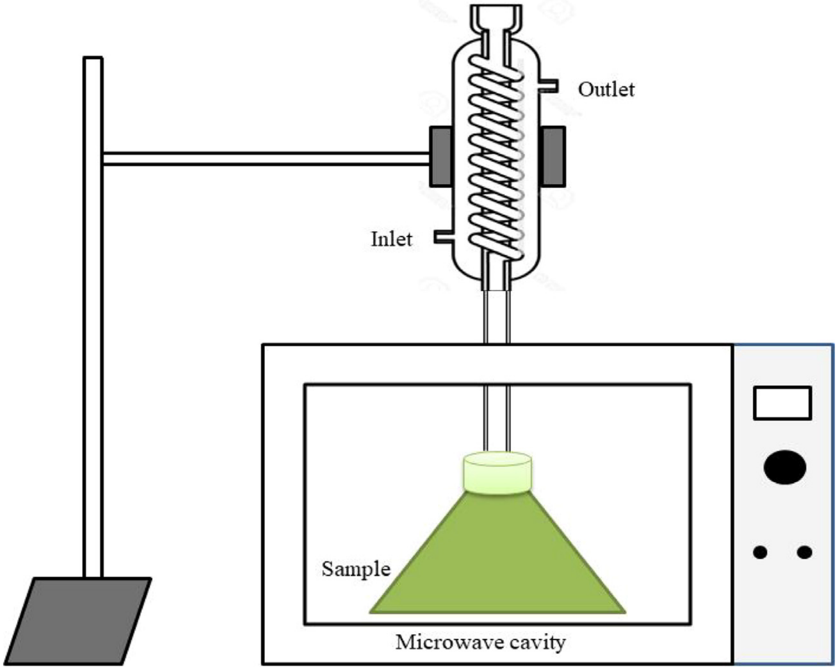

Fig. 4. Schematic flow diagram of Microwave-assisted extraction.

containing various amounts of PL (pectin lyase), PG (polygalacturonase), PME (pectin methylesterase), hemicellulase, and cellulase. Enzyme-assisted extraction has been successfully been applied for the extraction of polyphenolic compounds from the various plant matrices, such as apple skins, press residue of black current, and grape skins (Tomaz et al., 2015). The main advantage of enzyme-assisted extraction is that it offers a green, novel, and safe approach for the extraction of bioactive compounds. The effects of tannase were investigated by Chamorro and his team (Chamorro et al., 2012).

The extraction of lipids (Jin et al., 2012), bioactive by plants, and oils (Huo et al., 2015) is also been reported by using enzyme-assisted extraction. The mechanism of enzyme activity plays a major role in the process of enzyme-assisted extraction because of its nature of selectivity. The technique is the first instance is dependent upon the ability of the enzyme to hydrolyze the cell wall and disrupt the complex cell wall structure. This allows the release of compounds in the bulk solution (Gardossi et al., 2009). The enzyme–substrate complex is formed, causing stress and strain on the substrate, which results in the promotion of hydrolytic reactions (Sowbhagya and Chitra, 2010).

4.9. High voltage electric discharge (HVED)

Another extraction technique that recently evolved was high voltage electric discharge (HVED). This technique works on the application of a high voltage between two electrodes. The electrons are accelerated and excite water molecules when they reach sufficient energy. A flood of electrons is created, known as a streamer. The streamer propagates from the positive to the negative electrode if the intensity of the applied electric field is increased. Electrical breakdown occurs when one of the streamers attains the negative electrode. High-amplitude pressure shock waves, liquid turbulence, bubble cavitation occurs during such an electrical breakdown. This phenomenon leads to the fragmentation of particles and damage of cell structure that enhances the extraction of the intracellular compounds (Boussetta et al., 2009). The advantages of HVED are that by using this technique, the optimum conditions for the recovery of phenols are being established at pilot scales (Boussetta et al., 2011, 2012a,b).

Using the different cut-offs of variation in molecular weight, the concentration of extracts which are obtained from the HVED treatment of grape seeds can be carried out (Liu et al., 2011). In a study conducted by some researchers, it was stated that during the extraction of polyphenols from Chardonnay grape skins, the extraction time was reduced from 180 min to 60 min by using the HVED extraction technique (Boussetta et al., 2009). The HVED shows the maximum results in tissue-damaging, providing in the increased yield of protein and polyphenol from grape vine shoots as compared to ultra-sonication and PEF (Rajha et al., 2014a,b). The main aim for the development of this technique leads to the extraction of polyphenols and the total soluble matter from grape pomace into distilled water.

4.10. Miscellaneous extraction techniques

Pulsed ohmic heating is also known as the combination of electrical and thermal treatments that can be recognized to be an effective extraction method. Due to the application of electric current, heat is generated which speeds up the phenol extraction from grape pomace. As the temperature increases, there is an increase in the electric field resulting in the permeabilization of the cell membrane. The freeze-thawed samples were more susceptible to cell damage. The 400 V/cm electric strength with 30% of ethanol as a solvent is provided for the maximum yield of polyphenols (El Darra et al., 2013).

Another technique is also known as high-pressure processing (HPP) is used for the extraction of thermolabile compounds. It is a non-thermal technology in which high pressure between 100–1000 MPa is applied. The increase in temperature causes changes in the structure of the cell because of the disturbance of the salt bridges and deprotonating of the charged groups. The permeabilization of the cell membranes increases, resulting in the release of cell extract in the solvent. Because of the transfer of uniform pressure, the extraction is obtained at a fast rate (1–2 min). The extraction time is decreased because of increased pressure. In a study, the extraction yield of anthocyanins was increased threefold through HPP (Corrales et al., 2008a,b). The studies of various parameters for anthocyanin extraction from red grape pomace showed the highest yield at an ethanol concentration of 50% at 600 MPa and 70°C (Corrales et al., 2009). The encapsulation of phenolic compounds extracted from grape pomace with the use of the HPP technique was done (Sessa et al., 2013). The oxygen radical absorbance capacity and fluorescence recovery were carried out for evaluating the antioxidant activity of phenol.

One of the other techniques is deep eutectic solvents or DESs which are made by using two or more components by heating at the temperature of 80°C or by lyophilizing (Gutierrez et al., 2009). In a study, the extraction of anthocyanin was carried out from grape skin using DES. It utilized maltose and citric acid and proved to be the green extraction method (Jeong et al., 2015). In another study conducted by Bubalo et al. (2016), it was stated that phenolic components were extracted using the DSE technique by using choline chloride with oxalic acid.

5. Comparative study of technology selections for the valorization of grape pomace

For extracting the bioactive compounds, the major objective of green technologies is to gain a faster rate of extraction and more effective use of energy from natural sources i.e. winery wastes and by-products. It reduces both, the size of the equipment and the number of processing steps when an increase in mass and heat transfer and preserves the natural environment and its resources (Soquetta et al., 2018). It has been noted that the use of PLE results in the greater yields of phenolic and anthocyanin in the non-conventional technologies, and as compared to supercritical fluid extraction (SFE) after analyzing pomace, it provides extracts with advanced antioxidant capacities from different varieties of grapes (Otero-Pareja et al., 2015). The PLE technique is used to increase the efficiency of the extraction process, which is based on increased temperatures and pressures.

The extraction kinetics is enhanced by increasing the temperature and by maintaining the solvent condition. This results in the decrease desorption kinetic rate and its increase in the solubility of the analytes from the sample matrix. In this way, this accelerates the extraction procedure and reduces overall solvent consumption as well as the sample preparation time. Palma et al. (2002) have previously demonstrated the stability of phenolic compounds using superheated solvents with grapes. In line with this observation, at three temperatures (80, 100, and 150 °C), Solyom et al. (2014) studied that the grape marc obtained by using simulated degradation under isothermal heating was found to be more sensitive. This phenomenon was also confirmed by the analyses of the antioxidant activity and the total phenolic content.

6. Applications or use of grape pomace

6.1. Antimicrobial effects

Due to environmental and health concerns, attention is been increased on obtaining compounds from natural sources such as vegetables and fruits rather than using antimicrobial compounds of synthetic origin. The antibacterial properties are present in the phenolic substances due to the deprivation of iron or hydrogen bonding with the microbial enzymes or the vital proteins (Kabir et al., 2015; Sanhueza et al., 2014). The naturally occurring phenolic compounds, flavonoids, include anthocyanins, leucoxanthins, flavonoids alkaloids, and anthoxanthins (Fig. 5). Flavonols are considered the main phenolic compounds in grapes with antimicrobial potential. They show synergistic effects with antibiotics, besides being able to inhibit virulence factors (Daglia, 2012).

Nazer et al. (2005) stated that phenolic compounds act on the membrane of the microbial cell. They cause derangement in the structure and function of the membrane by accumulating in the lipid bilayer. They exert inhibitory activity in the cell cytoplasm by penetrating the bacterial cell, thereby leading to lysis and releasing of intracellular ATP. The cell constituents can also be lost because of the increase in the cytoplasmic membrane permeability. The antibacterial activity could also be related to a 3,4,5-trihydroxifenyl group structure that can be found in epigallocatechin, epigallocatechin-3-O-gallate, castalagin, and prodelphinidin, which can be essential for the safety of food.

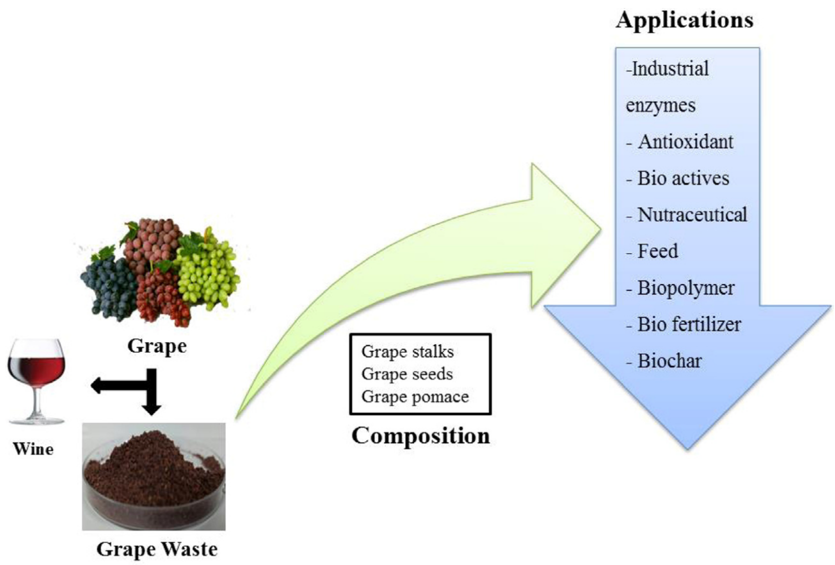

Fig. 5. Grape winery waste composition and its applications.

Flavonoids interact with soluble extracellular proteins and bacterial cell walls, possessing antibacterial activity, resulting in cell death (Natalia De et al., 2018). The phenolic-rich fruit-based extracts' antimicrobial potential is dependent on the pH and solubility of the extracts. The phenolic non-pigmented polymers have anti-listerial activity and are non-pH dependent while phenolic pigmented polymers are pH-dependent and exhibit anti-listerial activity. In a study by Dias et al. (2018), it was shown that probiotic bacterium is being used as a bio-preservative for food applications. In this study, the whole grape pomace which represents a supplementation of dietary fiber was utilized as the source of polysaccharides. It can be used as a possible prebiotic function that enhances the probiotic population.

6.2. Antioxidant properties

The antioxidant activity can be considered as one of the most remarkable phenolic compound's bioactivity from grape pomace. It is dependent on the number of hydroxyl groups present in the specific molecule and its activity could be boosted by steric interference or hindrance. The electrons pull out the nature of the carboxylate group in benzoic acid creating a privative effect on the hydrogen giving capabilities of the hydroxy benzoates. According to Kabir et al. hydroxylated cinnamates are much beneficial than their counterparts of benzoate (Kabir et al., 2015). The phenolic substances' antioxidant capacity could act as hydrogen donators, metal chelators, free radical scavengers, and quenchers of singlet oxygen. The antimicrobial agents and the antioxidants aim at increasing the stability of the products and their shelf life. These are used in food industries for the preservation of food for a longer period and increasing its quality and safety. Due to certain negative effects of synthetic additives, consumers are more aware now, which has resulted in stimulating the search for antioxidants and antimicrobials from natural foods (Chou et al., 2007).

In various studies, it is studied that grape seeds provide good kidney and liver protection through regulating bcl-XL gene, from acetaminophen overuse of which damages the DNA and reduces oxidative stress. It was observed that bioavailability was found in both in vitro and in vivo models for grape seed phenolic extracts (GPSE). It was significantly more useful in the protection against the DNA damage, free radicals, and free radical-induced peroxidation of lipids. The potential of antioxidant attributes to phenolic compounds can be related to the free radical inactivation by electrons and hydrogen transferring reactions (Urquiaga and Leighton, 2000).

In the oxidation reaction of lipids, there are three main stages involved which namely are initiation, propagation, and termination. These lead to the formation of hydroperoxides, volatile substances (such as ketones, alcohols, aldehydes), and free radicals, which are in charge of the rancidity and off-flavor symptoms or characteristics (McClements et al., 2010). The initiation phase can be suppressed and/or the propagation phase can be stopped by the antioxidants, by reducing the catalyst metal availability or by sequestrating the free radicals from the system (Brewer, 2011). Additionally, antioxidants can act in the concentration of oxygen, hence preventing them from peroxide formation or stopping the reaction. The property of the best antioxidant is that they generally act by interfering with the chain reaction (Brewer, 2011). The capacity of antioxidants varies in different phenolic compounds (Maqsood et al., 2014).

6.3. Anticancer effects

Grape pomace is generally utilized for the enhancement of dietary supplements, as it is a rich source of phenolic compounds. In cell line models, several mechanisms are developed in which grape seed extract showed uncommon anti-tumoral activity in breast, bladder, leukemia, prostate, colon, and lung tumors (Dinicola et al., 2014). Under in vitro conditions, low doses of proanthocyanidins obtained from grape seed inhibit liver cervical (HeLa) and (HepG2) growth of cells (Apostolou et al., 2013). By modulating the redox balance, grape seeds are helpful in the inhibition of cancer by showing both pro-oxidant and antioxidant action.

Additionally, MAPK kinases, NF-kB, metalloproteinases, cytoskeleton proteins, PI3K/Akt, and up-and-down-regulations appear too coordinated by grape seeds. Recently, researchers studied and provide evidence in which it was stated that in hepatocarcinoma, by stimulating inhibiting cell proliferation, apoptosis, and inflammation blocking, a presumable anti-cancer shielding effect is introduced by the grape seeds extract (Hamza et al., 2018).

In a study conducted by Del Pino-García et al. (2016), the potentiality of grape marc was analyzed as a chemoprotective agent for colorectal cancer. Another study stated that in the small intestine, phenolic acids which were obtained from the seedless red wine pomace were more bioavailable, as compared to grape seeds which were easily fermentable in the colon.

A chemoprotective effect was seen by treatment with red wine pomace seasonings through attenuation of oxidative DNA damage in colon cancerous cells. The *in vitro* studies show a possible therapeutic effect of grape seed extracts. The clinical research could verify the safe pharmacological use for this purpose (Dinicola et al., 2014). One more study proposes the characterization of the underlying mechanism and acute lymphoblastic leukemia in Jurkat cells, and investigation of the anticancer effect of a purified white grape pomace extract (PWGPE) (León-González et al., 2017).

6.4. Animal feed

In the previous years, researchers reported that 3% of the total grape marc is used as feed for animals (Dwyer et al., 2014; Brenes et al., 2016; Taranu et al., 2017). In a study, the diet including grape seeds did not show any change in the performance of the pigs but it suppresses the protein expression of the regulatory molecules by reducing the yield of some inflammatory cytokines(IL-8, IL-1β, IFN-γ, and TNF-α) in the liver of pigs. In the diet of pigs, the addition of fermented grape pomace increases the color constancy of meat and total polyunsaturated fatty acids (PUFA) in the hypodermic animal fat while decreases the peroxidation of lipids. Other than studies on pigs, the addition of grape pomace in cow feeds increases the concentration of polyunsaturated fatty acids (PUFA) in milk and changes the composition of the ruminate bacterial community thus improving the health of cows (Moate et al., 2014). Another report from Ebrahimzadeh et al. (2018) showed that the increment of grape pomace in the broiler diets increases the immune response and antioxidants of broiler chickens and reduces the feed cost per kg of live weight. No effects were seen on the performance of the chickens. A decided amount of grape pomace when supplemented with feed, affects the piglet productivity, microbial biota, and redox potential, following the hypothesis that there might be a significant effect of feed GP on animal health through improvement of different antioxidant mechanism in piglets tissues and blood (Chedea et al., 2019; Kafantaris et al., 2018).

6.5. Compost fertilizer

A biotechnological development in which polymeric material occurring inorganic wastes are broken down by hydrolytic enzymes that are liberated by thermophilic and mesophilic micro-organisms throughout the mineralization process under aerobic conditions is called composting (Azim et al., 2017). Usually, grape pomace because of its possible pathogenicity could not be directly applied to the soil as it is a heterogeneous blend of pulp, stalks, seeds, and skins. Therefore, at first, composting should be carried out before using it as a soil conditioner. In modern greenhouse agriculture and horticulture, low-cost composts which are produced from winery wastes have given favorable results by reducing environmental stress. Majorly, due to the low amount of phosphoric acids and nitrogen, grape pomace has certain values and can be used as an organic fertilizer (Table 3). Based on winery waste variety, chemical analyses of the compost comprised of various elements like Zn, Mg, Fe, Ca, and heavy metals such as Cr, Ni, Cd, Pb. Therefore, by recovering the heat and CO_2 produced during composting, it could slowly replace the chemical fertilizers (Ferrer et al., 2001).

Grape marc is an organic waste material that can be composted and used for the amendment of soil and as an organic fertilizer for increasing the quality of soil and production of grapes. The stabilization and the maturity of the compost show the potential use of the amendment of organic wastes (Martínez Salgado et al., 2019). These two characteristics of compost i.e. maturity and stability define the quality of the compost in which the term stability relates to the conversion of primary unsteady organic matter to the durable matter (Martínez Salgado et al., 2019; Gonzalo et al., 2016; Martínez et al., 2016).

Table 3
Products derived from grape pomace, used conditions, and yields.

S. No.	Products	Conditions	Yields	References
1.	Bio-char	Pyrolysis at 300—500 °C	30.8 - 33.8%	Ibn Ferjani et al. (2020)
		Pyrolysis at 300 —700 °C	66.5% Pb removal	Jin et al. (2020)
		Pyrolysis at 300 °C	–	Manolikaki and Diamadopoulos (2016)
		Pyrolysis at 300 °C for a period of 1 h	155%	Manolikaki and Diamadopoulos (2019)
		Pyrolysis at 500 °C	–	Duman et al. (2018)
		Pyrolysis at 300 °C	–	Manolikaki and Diamadopoulos (2020)
2.	Industrial enzymes	Acid hydrolysis	Minerals and amino acids	Chikwanha et al. (2018b)
		Ultrasonic bath	–	Minjares-Fuentes et al. (2016)
		Solid state fermentation	Polygalacturonase and tannase enzymes	Teles et al. (2018)
		Enzyme-assisted extraction and high hydrostatic pressure	Proanthocyanidins	Teles et al. (2018)
		Aspergillus niger B60 mycelium	Enzymes	Papadaki et al. (2020)
		Fermentation with *Kluyveromyces marxianus*	–	Williams et al. (2019)
3.	Bioactives	45 °C, pH- 5, time- 2hrs	66%	Meini et al. (2019)
		56 °C, time-20 min	48.76 mg/gm	Drevelegka and Goula (2020)
		40 °C, 0.25%E/S at 30 min of extraction	∼50%	Montibeller et al. (2019)
		Solvent concentration 50%, temperature 50 °C and time 29.6 min	62.487 mg/gm	Dranca and Oroian (2019)
		Temperature 25–45 °C, incubation time 2 h (pH-5.0)	–	Meini et al. (2019)
		70% acetone, 29.9% mL water and 0.1% hydrochloric acid	Polyphenols and antioxidants	Chikwanha et al. (2018a)
4.	Bio fertilizers	550 °C for 4 h	–	Sanchez-Hernandez and Domınguez (2017)
		Biochar was prepared at 300 °C and mixed with soil	Increased the dry weight of plant by 59%–186%	Manolikaki and Diamadopoulos (2020)
		300—700 °C	33%	Ibn Ferjani et al. (2020)
		5 h at 550 °C	–	Gómez-Brandón et al. (2019)
		Biochar was prepared at 300 °C and mixed with soil	Dry wt. of maize increased by 75%	Manolikaki and Diamadopoulos (2019)
		Vermicomposting	–	Gómez-Brandón et al. (2019)
5.	Biofuels	160 °C for 3h	–	Allison and Simmons (2018)
		288 to 322 °C	40%	Khiari and Jeguirim (2018a,b)
		5 min at100 °C	–	Jin et al. (2018)
		500 °C	14%	Zhang et al. (2017)
		Hydrothermal carbonization	–	Basso et al. (2016)
		Co-pyrolysis of grape seeds and polystyrene	–	Sanahuja-Parejo et al. (2018)

6.6. Dietary fiber

Carbohydrates polymers in which more than ten monomeric units are present and which are not hydrolyzed by the endogenous enzymes present in the small intestines of humans are defined as dietary fibers (Joint FAO/WHO, 2010). The major importance of using dietary fiber is that it helps in the protection against cancer, boosting of food movement through the digestive system, cardiovascular diseases, decreasing blood cholesterol, prevention of diabetes

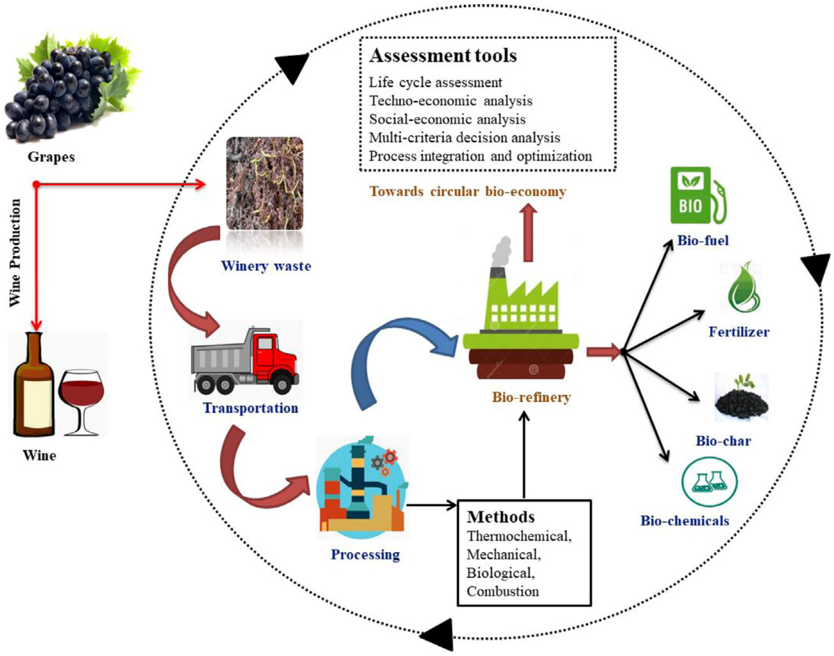

Fig. 6. Bio-refinery model and sustainable technologies in the scope of economy and circular bio-economy.

due to adsorption attenuation of glucose, obesity prevention, and constipation (Deng et al., 2011; González-Centeno et al., 2010; Llobera and Cañellas, 2008). Cereals, vegetables, and fruits are the source of dietary fiber with a recommended consumption intake of 25–30 g/day as per the guidelines (FDA, 2013). However, this ingestion is a need for alternative sources and also not easily achieved. It has encouraged the expansion of many supplements and commercial fiber-rich products (Llobera and Cañellas, 2008; González-Centeno et al., 2010). The phenolic components present in the dietary fiber comprise a large number of health benefits, including the reduction in the risk of chronic diseases and maintaining intestinal health (Beutinger Bender et al., 2020; León-González et al., 2017; Macagnan et al., 2016).

Grape skin consists of a large quantity of hemicellulosic sugars, which is a complex lignocellulosic material that produces a mixture containing a large variety of monomers of glucose and xylose (Devesa-Rey et al., 2011). In grape pomace, the monosaccharide composition is broadly distributed and generally comprises of Arabinose (Ara), Galactose (Gal), Rhamnose (Rha), Glucose (Glc), Mannose (Man), Xylose (Xyl), and Uonic acid, Galacturonic acid (GalA) to a large extent (Beres et al., 2016; Ferreira et al., 2014; González-Centeno et al., 2010). Researchers reported that many more uses of grape marc are been developed besides the above-discussed point.

7. Circular bio-economy and techno-economic prospects

The concept of circular economy was encouraged by the re-assessment of production methods in the 1980s from the idea of industrial ecology and metabolism (Frosch and Gallopoulos, 2010). The bio-economy gained persuasively in Europe during the early 2000s. It has been defined as the manufacturing of various renewable biological resources and converting them to numerous value bio-based products which include feed, food, biochemical and bioenergy products (Fund et al., 2015). The circular bio-economy embraces the framework of the circular economy by consuming biomass as an essential component for the generation of various bioproducts, bioenergy, and bio-chemicals in a bio-refinery (European Commission, 2017). A biorefinery can be described as an infrastructure facility with conversion technologies such as biochemical, combustion, thermochemical, and biological, for the efficient production of bio-based products, e.g., bioenergy, biochemicals, biofuels, and other valued bio-products (Ferreira, 2017; Cherubini, 2010).

The various methodologies used for reviewing the sustainability of biorefineries are (1) Life cycle assessment, (2) Techno-economic analysis, (3) Social-economic analysis, (4) Multi-criteria decision analysis, and (5) Process integration and optimization. The performance of biorefinery is measured by the environmental evaluation through life cycle assessment (LCA), which is a descriptive method for accounting and evaluating the environmental impact of providing a service or production of a product based on the ISO 14040 series. LCA studies have been accomplished to justify the eco-friendly effects of bio-refinery configurations. From the perspective of the circular bio-economy, the LCA method used employs a cradle-to-grave system boundary which could be an important factor in the comprehensive design of a biorefinery, recognizing and increasing the chances of improvement (Nizami et al., 2017) (see Fig. 6).

Techno-economic analysis can be defined as the evaluation of technical and economical aspects in the manufacturing of a product (Lauer, 2008). It includes the quantification of operational and capital costs by considering the technologies included and involved in the bio-refinery. Food wastes possess a high level of potential and homogeneity; therefore they could be used as the feedstock in the biorefineries for the production of value added products and chemicals (Matharu et al., 2016; Ong et al., 2017). The execution of the concept of biorefining of the grape pomace is sternly dependent upon the process screening and certainty issues which could be carried out based on benefiting the environment, socio-economic aspects, and competitiveness of cost.

The socio-economic impact is not only limited to the manufacturing of the bioenergy products in the biorefinery, but it is also outspread to the farms where the cultivation and growth of biomass take place. The social life cycle assessment is used for examining the social dimension of the rural biorefinery (Hasenheit et al., 2016). Multi-criteria dimension analysis is a decision-making tool capable of enabling the accumulation of several criteria that aims to the development of a complete and combined assessment tool. It is capable of implementing the life-cycle assessment and social-life cycle assessment methodologies covering the bottom line of the framework (Cinelli et al., 2014). In 2019, Lemire et al., coupled multi-criteria dimension analysis with a geographic information system (GIS) to design and evaluate the decentralized bio finery supply chain in Canada resulting in the average time travel of the materials and products. Process integration and optimization can be defined as a holistic framework in the application of the techniques for integrating various conversion processes. It requires the reduction of material and energy consumption while supplying the production necessities and minimizing the waste and emissions (El-Halwagi, 2013).

The evaluation of techno-economic in biorefining mainly focuses on the production of various products from waste generated from wine industries by succeeding the cascade principles for feasible accessibility of the scale-up process. In a study reported by Dimou et al. (2016) the refining process of wine lees for the production of four different products (Ethanol, calcium tartrate, antioxidant-rich extract, and yeast cells) is studied and it is observed that for the development of a profitable refining scheme, the wine lees processing capacities of about 500 to 5000 kg/h would be required considering 120 days of the annual operating time. The sensitivity of this analysis was to analyze the capacity of the plant for the development of cost-competitive processes which can utilize winery waste product for the production of various products with versatile market outlet. In another study reported by Todd and Baroutian (2017), the techno-economic evaluation was carried out for the extraction of bioactive phenolic compounds from grape marc using different extraction techniques like an organic solvent, subcritical water, and supercritical CO_2 and comparing the manufacturing cost reported NZ$89.60/ kg product and cost of extraction techniques NZ$87.0/ kg product; resulting in overall less profit. In a study conducted by Akbari et al. (2020), wet torrefaction was used for the processing of elevated-moisture content waste for the production of solid-coal products from five different biomass feedstocks (grape pomace, pine, wheat straw, pine, algae, and animal manure). The models for the process are developed for every biomass and the techno-economic assessment was conducted. The results of the study showed that the lowest production costs were achieved through wet and dry torrefaction of grape pomace at 4.14$/GJ and 2.29$/GJ, respectively. Another study reports the analysis for the determination of environmental and economic viability of solid organic waste from the wineries. The processes were executed which include generation of electricity by combustion process and production of bio-oil, bio-gas, and char by pyrolysis (Khan et al., 2020). The data generated by the simulations were used for the environmental and techno-economic evaluation. It was reported that pyrolysis was found to be the superior method for the utilization of grape pomace, yielding 151 kg of biochar and 140 kg of bio-oil per tonne of grape pomace (Zhang et al., 2017). The study of feasibility and scale-up were reported for the initiation and production of grape seed oil by the supercritical CO_2 extraction technique. The determination of scale-up factors and cost is carried out by the implementation of experimental evaluation and modeling results. The results indicate that the economic feasibility with points of about US$ 7.46 per kg-oil and a 28% return rate on investment (Duba and Fiori, 2019). In another study by Cortés et al. (2019) by using wine lees, a sensitivity analysis was conducted. Considering that the production of a wine bottle generates 11.48 mL of wine lees approximately. The profit of €0.022 was generated by the sale of these products. As compared to other products, wine lees showed the best results in environmental assessment as it does not require a large amount of consumption of chemicals and electricity. Nevertheless, there are still chances for improvement and future research.

8. Future research prospects

For wineries to reduce environmental contamination, the sustainable capitalization of grape pomace could be a beneficial policy and in the whole production process, they use as a substitute for the reduction of carbon footprint. With certain steps of extraction and purification, simplified processes could be the preference with aiming an easy scale-up in this sense, as well as also by accomplishing an economical production. Grape pomace extracts are a relevant point achieved by the characterization in terms of elongating the cost-effective value of the gained product. During the application of extracts, knowledge of the recognition and individual concentrations of the extracted or recovered phenolic after extraction is a considerable fact. In diverse industries, provided tools will endorse the technological application by this information of recovered bioactive components (Table 3). Also, the employment of modern detectors could affect the antioxidant properties of extracts that could be a beneficial way for the identification of unknown compounds.

9. Conclusions

In agriculture and agro-industrial process disposal or management of waste materials are serious concerns. The recovery of high-value compounds from grape pomace is a challenging issue in food processing industries. The wine production industries are responsible for a substantial part of the environmental concern as they dispose of waste in an open environment. To mitigate or overcome the environmental issues researchers have to develop extraction techniques, which recover the value-added product from the wine waste. In this review, the available information on the utilization of winery waste is showing a potential option or substitute for waste management. Alternative technologies are emerging to recover high-value-containing products from winery waste, to promote efficient and greener technology. In the subject of winery waste, further research and practical experimentations are necessary, since a very limited amount of studies have been conducted and analyzed about the cost of the use of winery waste.

CRediT authorship contribution statement

Talat Ilyas: Writing - original draft. **Pankaj Chowdhary:** Writing - original draft. **Deepshi Chaurasia:** Writing - original draft. **Edgard Gnansounou:** Writing, Reviewing. **Ashok Pandey:** Reviewing, Editing, Conceptualization. **Preeti Chaturvedi:** Reviewing, Editing, Conceptualization.

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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