

Bioactive compounds and its optimization from food waste: review on novel extraction techniques

Subhamoy Dhua

Department of Food Engineering, NIFTEM, Kundli, India

Kshitiz Kumar

Department of Food Process Technology, ADIT, Vitthal Udyognagar, India, and

Vijay Singh Sharanagat and Prabhat K. Nema

Department of Food Engineering, NIFTEM, Kundli, India

Abstract

Purpose – The amount of food wasted every year is 1.3 billion metric tonne (MT), out of which 0.5 billion MT is contributed by the fruits processing industries. The waste includes by-products such as peels, pomace and seeds and is a good source of bioactive compounds like phenolic compounds, flavonoids, pectin lipids and dietary fibres. Hence, the purpose of the present study is to review the novel extraction techniques used for the extraction of the bio active compounds from food waste for the selection of suitable extraction method.

Design/methodology/approach – Novel extraction techniques such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, supercritical fluid extraction, pulsed electric field extraction and pressurized liquid extraction have emerged to overcome the drawbacks and constraints of conventional extraction techniques. Hence, this study is focussed on novel extraction techniques, their limitations and optimization for the extraction of bioactive compounds from fruit and vegetable waste.

Findings – This study presents a comprehensive review on the novel extraction processes that have been adopted for the extraction of bioactive compounds from food waste. This paper also summarizes bioactive compounds' optimum extraction condition from various food waste using novel extraction techniques.

Research limitations/implications – Food waste is rich in bioactive compounds, and its efficient extraction may add value to the food processing industries. Hence, compressive analysis is needed to overcome the problem associated with the extraction and selection of suitable extraction techniques.

Social implications – Selection of a suitable extraction method will not only add value to food waste but also reduce waste dumping and the cost of bioactive compounds.

Originality/value – This paper presents the research progress on the extraction of bioactive active compounds from food waste using novel extraction techniques.

Keywords Food waste, Bioactive compounds, Novel extraction methods

Paper type Literature review

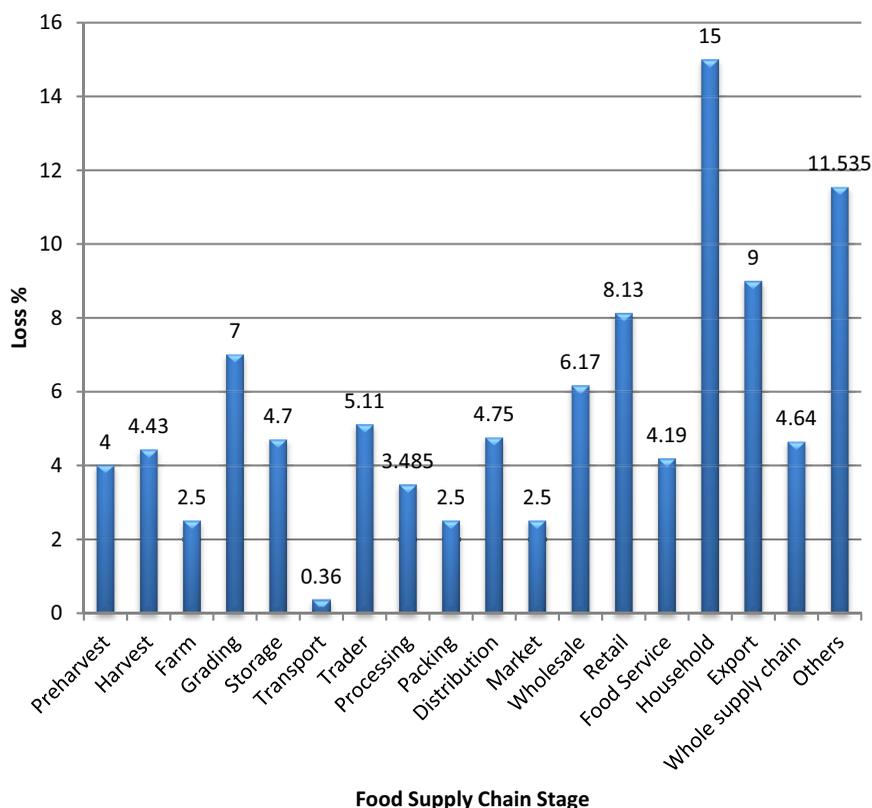


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Introduction

The terms “food loss” and “food waste” are used to indicate the food lost, discarded or degraded in the food supply chain from farm level to household level. *Food loss* is the decrease in the quantity or quality of food in the upstream of the food supply chain, i.e. at the production, post-harvest and processing stages. *Food waste* is the decrease in the quantity or quality of food in the downstream of the food chain, i.e. at the retail, food services and consumer levels (Teuber and Jensen, 2020; FAO, 2019). According to above two definitions, inedible parts of food such as bran and seeds are not included as either food waste or food loss. Later, the definition of food waste was modified to include the inedible part as “food and the associated inedible parts removed from the human food supply chain in the retail, food service and household level” (UNEP, 2021). Food waste has also been defined as “food (including inedible parts) lost from the food supply chain, not including food diverted to material uses such as biobased products, animal feed, or sent for redistribution”. The food lost and wasted at any level of the food supply chain is indicated by “food loss and waste” (Figure 1). At global level food loss and waste is estimated between 194 and 398 kg/per person/year (Corrado and Sala, 2018). In developed countries, highest amount of food waste



Note: Adapted from Food and Agricultural Organization of United Nation’s Food Loss and Waste Database’s Boxplot by stage

Figure 1.
Global percentage
food loss at different
levels of the food
supply chain

is contributed by the household activities (42%). Moreover, 39%, 14% and 5% of food waste is contributed by manufacturing industry, food service sector and distribution, respectively (Galanakis, 2018). In developing countries, the major food loss and waste occur at post-harvest and processing levels. *Food by-products* is a term that is used to indicate the secondary, less-revenue-generating stream generated during the preparation of the main food product. *Food by-products* can be defined as “the waste generated during processing of food products in the industry and not for other purpose or recycled” (Kumar, 2020). These by-products differ on the basis of food being processed, for example, rice bran from cereal processing, skin from the meat industry, whey from the dairy industry and peels from the fruit industry. In the current paper, waste refers to by-products of fruit and vegetable industries including the inedible parts.

Fruits and vegetables (F and V) form a large part of human meal because of the presence of health beneficial components like dietary fibres, antioxidants, vitamins and minerals. Change in lifestyle and increased demand of processed and packaged food products have increased the processing requirement of fruits and vegetables. During processing of F and V, e.g. peeling, cutting, drying, pasteurization, milling, extrusion, mixing and cooking, significant amounts of valuable compounds are lost with the F and V by-products. The fraction of slighted materials in most of the fruit processing industries is high (e.g. citrus, 30%–50%; pomegranate, 40%–50%; mango, 30%–50%; and banana 20%) (Faustino *et al.*, 2019). Depending upon the location and harvesting method, around 30% of food loss and waste is generated by the fruits processing industry (Wadhwa and Bakshi, 2013). F and V together constitute around 50% of the total food loss and waste (Figure 2). Fruit and vegetable industry by-products include peels, stems, seeds, shells, bran and trimmings. These by-products are a very good source of bioactive compounds such as pectin, dietary fibres, hemicelluloses, essential oils, flavours, enzymes, proteins, antioxidants and phenolic compounds. Effective use of large amounts of F and V waste is a major challenge for the producer and processor. Selection of a particular F and V by-product for their utilization is done on the basis of the presence of valuable bioactive compounds in them (Marić *et al.*, 2018). The functional ingredients from F and V waste can be extracted by various traditional and novel extraction methods (Roselló-Soto *et al.*, 2016; Zhu *et al.*, 2016). Traditional extraction methods such as solid-liquid extraction, soxhlet extraction and liquid-liquid extraction are used to extract the bioactive compounds from food biomass

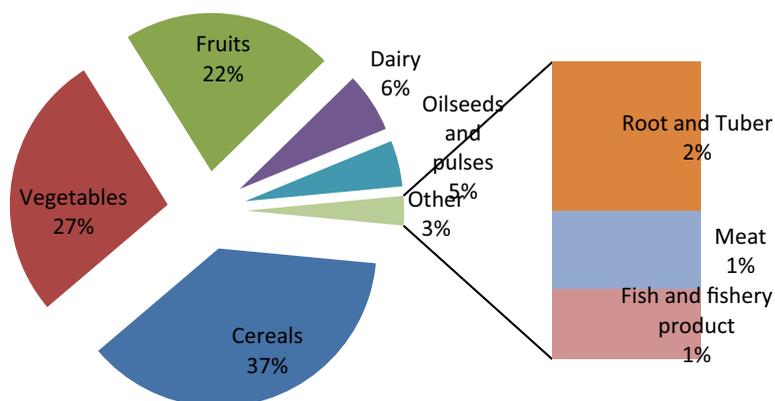


Figure 2.
Contribution of
different food groups
in food loss and waste

Source: Adapted from: Kosseva, 2020

waste streams at the initial stage of extraction. The traditional methods are associated with some disadvantages like high solvent consumption, high energy requirement, thermal degradation of heat-labile components and longer extraction times, whereas the novel extraction processes, which include ultrasound-assisted extraction (UAE) (Li *et al.*, 2022; Daud *et al.*, 2022; Savic *et al.*, 2022), microwave-assisted extraction (MAE) (Araújo *et al.*, 2020; Alvi *et al.*, 2022; Zin and Bánvölgyi, 2022), enzyme-assisted extraction (EAE) (Patil *et al.*, 2021; Teles *et al.*, 2021; Nath *et al.*, 2016), supercritical fluid extraction (SFE) (Peng *et al.*, 2020; Pattnaik *et al.*, 2021; Restrepo-Serna and Alzate, 2022), pulse electric field extraction (Redondo *et al.*, 2018; Pataro *et al.*, 2020) and pressurized liquid extraction (Sagar *et al.*, 2018; García *et al.*, 2021; Pereira *et al.*, 2021), are more reliable and efficient compared with traditional methods.

The transfer from a traditional solvent-based process to a novel, zero-waste process drives the development of greener methods, and there is a need to summarize all the novel methods and their operating parameters for the extraction of bioactive compounds from food waste. A complete review focussing on the extraction of valuable bioactive compounds from food waste and by-products is currently not available. Hence, the objective of the present review is to provide comprehensive information on the recent research on the utilization of novel methods of extraction of high value-added compounds from F and V processing waste and by-products.

Novel extraction techniques

The utilization of food waste for the recovery of valuable bioactive compounds many a times is restricted because of lack of economically viable, energy-efficient and environmental friendly extraction techniques along with the capability to preserve the functionality of volatile bioactive compounds. The emergence of various non-thermal novel extraction techniques in the last two decades has overcome these limitations of conventional extraction techniques. Some of these novel extraction techniques discussed in following sections have been used to extract valuable bioactive compounds from food waste.

Ultrasound-assisted extraction

Ultrasound waves are mechanical waves having a frequency (>20 kHz) higher than the audible frequency range of human beings (20 Hz to 20 kHz). These waves consist of a series of compression and expansion cycles that can be propagated through solid, liquid or gas medium (Roselló-Soto *et al.*, 2015). The UAE technique is widely acknowledged as “green and innovative” because of its environment-friendly nature (Bhargava *et al.*, 2020). This technique decreases the operating and maintenance cost and allows reduction of wastes and elimination of hazardous substances (Daud *et al.*, 2022; Chemat *et al.*, 2017). The benefits of UAE include less energy and power usage, higher product yield, short processing time and less chemical usage over the conventional extraction methods such as solvent extraction (Barba *et al.*, 2015).

Acoustic cavitation is the main ultrasonic mechanism and refers to the formation, progression and breakdown of bubbles. When ultrasound waves propagate through liquid solution, the negative pressure force during the rarefaction phase exceeds the binding forces of the liquid molecules, thus creating the cavitation bubbles. On the next compression phase, these bubbles, which have grown in size because of coalescence, collapse, creating extreme energy and leading to fragmentation, localised erosion, pore formation and shear force high enough to break down the cell walls of plant tissue (Kumar *et al.*, 2021). This enables the solvent to penetrate into the plant material and helps to extract the intracellular contents (Chemat *et al.*, 2017). Ultrasound waves accelerate the mass transfer during the extraction process because of the effect of acoustic cavitation.

Some parameters like frequency (f), attenuation coefficient (α), amplitude (A) and wavelength (λ) are used to characterize the ultrasound. Pressure, sonication time, ultrasonic

power, temperature, solvent used, solvent-to-solid ratio and duty cycle are the other factors to be considered during the UAE process (Kumar *et al.*, 2021).

Different studies have reported on the use of ultrasound waves for pectin extraction from food waste. Moorthy *et al.* (2015) obtained the highest pectin yield (24.18%) from pomegranate peel by using an ultrasound device with an immersed sonotrode having a flat tip probe of 2 cm diameter. The optimum condition was found to be 20 kHz frequency, 130 W maximum power, solid–liquid ratio of 1.18 g/ml, an extraction time of 29 min, 1.3 pH and an extraction temperature of 62°C. The other highly explored food material for pectin extraction is grapefruit peel. A yield of 19.16%–27.51% has been reported for pectin from grapefruit peel (Bagherian *et al.*, 2011; Wang *et al.*, 2016; Xu *et al.*, 2014). Wang *et al.* (2016) and Xu *et al.* (2014) obtained nearly the same amount of yield, which was approximately 1.4 times higher than the yield reported by Bagherian *et al.* (2011). This increase may be attributed to the additional heating performed along with ultrasound treatment. Pectin extraction from grape pomace (Minjares-Fuentes *et al.*, 2014), tomato waste (Grassino *et al.*, 2016), passion fruit peel (Freitas de Oliveira *et al.*, 2016) and mango peel (Guandalini *et al.*, 2019) was also performed. Minjares-Fuentes *et al.* (2014) found that using an ultrasonic bath having a frequency of 37 kHz and a maximum power of 140 W, it is possible to obtain the maximum pectin extraction yield of 29.38% at a temperature of 75°C, with an extraction time of 60 min and a pH of 2.0. This yield value is 20% higher than the yield value obtained when the extraction took place without any ultrasonic assistance and the other condition remained the same as before. Grassino *et al.* (2016) reported that the conventional extraction method took 96 min more than UAE to obtain the same amount of yield. The yield value obtained by using UAE is 69.2% higher than the yield value obtained in the conventional extraction process. Freitas de Oliveira *et al.* (2016) reported that the pectin yield from passion fruit peel obtained by the UAE process was 1.6 times of the yield obtained by the conventional extraction process and the time taken by the UAE process was also less (10 min). Guandalini *et al.* (2019) found that by using UAE, pectin yield in mango peel was enhanced by 50% with respect to the conventional extraction process and the time taken by the UAE process was only one-third of the time taken by the conventional extraction process.

UAE of antioxidants from pomegranate peel was performed by Pan *et al.* (2012). They conducted the UAE process in two ways: continuous ultrasound-assisted extraction (CUAE) and pulsed ultrasound-assisted extraction (PUAE). In comparison with the conventional extraction method, the antioxidant yield was increased by 22% and 24% for PUAE and CUAE, respectively, and the extraction time was reduced by 87% and 90% for PUAE and CUAE, respectively. Phenolic compounds have also been extracted from the peels of orange (Savic *et al.*, 2022), mango (Guandalini *et al.*, 2019), malta (Nishad *et al.*, 2019) and jabuticaba (Rodrigues *et al.*, 2015), and the optimized extraction conditions were determined.

UAE of oil from papaya seeds was reported by Samaram *et al.* (2015). They got the highest amount of yield (23.3%) at a temperature of 62.5°C and extraction time of 38.5 min.

Microwave-assisted extraction

Microwaves are electromagnetic energy having a frequency range of 300 MHz to 300 GHz. The electromagnetic energy is transferred into heat energy through ionic conduction and dipole rotation (Alvi *et al.*, 2022). Electric field, generated by microwave energy, is responsible for the movement of particles. Microwave energy initiates the transfer of ions and electrons. As a result, it causes ionic conduction. Dipole rotation is due to the alternate displacement of polar molecules. Polar molecules always try to align with the existing electric field and hence they start rotating the moment they experience the force due to

electric field. These two mechanisms create synergy and accelerate the release of energy. As it is an internal heating process, it accelerates rapid material damage and increases the diffusion rate of the aimed material. As a processing tool, microwaves have played a significant role in food science and technology since the last two decades. Microwave has been used for MAE, drying of foodstuffs, micro-organism inactivation and enzyme inhibition and inactivation.

Microwaves are specially used for the processing of wastes and by-products of food processing industry (Sahin *et al.*, 2017). MAE is an innovative and green extraction technology and has combined with the conventional extraction techniques that involve solvents for extraction of different targeted compounds (Périno *et al.*, 2016). Owing to its moderate capital cost, good performance under atmospheric conditions and special heating mechanism, MAE is the leading and most widely accepted alternative technique to conventional extraction techniques. The benefits of the MAE process are: shortened extraction time, low energy consumption, increased yield, decreased use of solvents, retention of integrity of extracted compounds, extraction of both polar and non-polar compounds simultaneously, solvent-free extraction of some compounds such as oils, determination of analytes in small samples as low as 0.1 g and less safety hazard. All these advantages make MAE an environment-friendly extraction technology (Chemat *et al.*, 2017).

The MAE process consists of three consecutive steps: separation of the solute from the active sites of the sample matrix under increased pressure and temperature, diffusion of solvent across the sample matrix and redemption of solutes from the sample matrix to the solvent. In MAE, the heat splits the cell walls by the expansion mechanism and the desired valuable compounds are diffused through the porous cell wall towards the cooler solvent. MAE is used to extract valuable bioactive compounds such as pectin, phenolic compounds, mannans and carotenoids from various food materials and is one of the major interest areas of several research groups.

Different studies have reported on the use of microwaves for pectin extraction from sour orange peel (Hosseini *et al.*, 2016a), pomelo peel (Chen *et al.*, 2016), passion fruit peel (Seixas *et al.*, 2014), banana peel (Swamy and Muthukumarappan, 2017), dragon fruit peel (Thirugnanasambandham *et al.*, 2014; Tongkham *et al.*, 2017), orange peel (Maran *et al.*, 2013), watermelon rinds (Maran *et al.*, 2013), papaya peel (Maran and Prakash, 2015), pumpkin biomass (Košťálová *et al.*, 2016), sugar beet pulp (Li *et al.*, 2012), dried apple pomace (Wang *et al.*, 2007) and citrus peel (Pfaltzgraff *et al.*, 2013).

Citrus fruit peels are one of major sources of pectin, and hence extraction and increase in yield with MAE coupled with reduction in extraction time has been reported. Different authors have delineated the optimized condition for pectin extraction from citrus fruit by-products through MAE. Maran *et al.* (2013) found 422 W microwave power, 1.4 pH, 2.82 min extraction time and 1:16.9 g/mL solid-liquid ratio as the optimum conditions for maximum pectin yield of 19.24% from orange peel. Pfaltzgraff *et al.* (2013) concluded that for citrus peel, the condition for highest pectin yield (10.8%) was 120°C temperature, 300 W of power and 10 min of time. Seixas *et al.* (2014) used microwave oven with at power levels of 356, 450 and 627.9 W for pectin extraction from passion fruit peel. They found that for MAE carried out by using tartaric acid and acetic acid, the yield increases by 56.13% and 26.57%, respectively. However, for MAE carried out by using nitric acid, the yield obtained was nearly same as the conventional extraction process. Time is one of the major factors that differentiated these two types of extractions processes from each other. The time taken by the conventional extraction process was 4.4 times greater than the time taken by the MAE process. Thirugnanasambandham *et al.* (2014) used an ordinary household microwave oven to extract pectin from dragon fruit peel. The authors found that using microwave power of

400 W, temperature of 45°C, solid–liquid ratio of 24 g/mL and extraction time of 20 min, the highest pectin yield (7.5%) can be obtained.

Hosseini *et al.* (2016) got maximum pectin yield (29.1%) from sour orange peel at 700 W microwave power, 1.5 pH and 3 min extraction time. Chen *et al.* (2016) performed two-stage microwave extraction of oil and pectins from pomelo peels: the first one was solvent-free microwave extraction for the extraction of oil and the second one was hot solvent microwave extraction (HSME) for the extraction of pectin where the microwave power, extraction time and solvent pH were varied. HSME took the least amount of time compared with the conventional acid solution extraction process. The time was reduced by 93.78% and the yield was increased by 3.29% for HSME in comparison with the conventional process. The optimal conditions of HSME for pectin was found at 520 W microwave power, 1.5 solvent pH and 5.6 min extraction time. Tongkham *et al.* (2017) performed the MAE process according to Seixas *et al.* (2014) with some modifications to extract pectin from dragon fruit peel. The authors concluded that 450 W microwave power and 5 min extraction time was the best condition to obtain the highest yield of 21.68% with less degradation. Hence, it can be observed through these studies that for the optimum extraction of pectin, the power requirement lies in range of 400–500 W, while time taken for the extraction lies in the range 3–20 min, which is marked improvement over conventional techniques.

Non-citrus fruits' by-products have also been used for the extraction of pectin with good success. Wang *et al.* (2007) concluded that the highest pectin yield (15.75%) from apple pomace was obtained at 1.01 pH, 499.4 W power, 0.069 solid–liquid ratio and 20.8 min time. Li *et al.* (2012) found that from sugar beet pulp, the highest pectin yield (32.4%) was obtained at 1.57 pH, 152.63 W of power and 3.53 min of time. Maran *et al.* (2014) reported that microwave power of 477 W, pH of 1.52, extraction time of 2.13 min and solid–liquid ratio of 1:20.3 g/mL were the optimum conditions for the maximum pectin yield of 25.79% from watermelon rind. Maran and Prakash (2015) concluded that microwave power of 512 W, pH of 1.8, extraction time of 2.33 min and solid–liquid ratio of 1:15 g/mL were the optimum conditions for maximum pectin yield of 25.41% from papaya peel. Košťálová, *et al.* (2016) observed that the pectin yield (7.1%) that was obtained from pumpkin biomass by MAE is nearly same as the yield (7.3%) obtained by the conventional extraction process. However, the time taken by the conventional extraction process was six times the time taken by the MAE process. Thus, it was observed that taking into account the extraction time, MAE is more advantageous than the conventional extraction process. Swamy and Muthukumarappan (2017) performed the CMAE process and intermittent microwave-assisted extraction (IMAE) of pectin from banana peel. A microwave oven, in which the power levels were changed from 300 W to 900 W, was used. In the IMAE process, they got the highest amount of yield (2.58%).

Attard *et al.* (2014) had performed MAE to extract D-limonene from orange peel. They performed MAE in a CEM II-Discover model where the microwave tube was exposed to 200 W of microwave power. They concluded that the yield (4.7%) obtained by conventional extraction was less than half of the yield (11.1%) obtained by MAE. Chiremba *et al.* (2012) used MAE to extract bound phenolic acid such as ferulic acid and *p*-coumaric acid from sorghum and maize bran. They observed that phenolic acid from sorghum was not associated with grain hardness, while that from maize was significantly associated with hardness.

Passos *et al.* (2014) recovered mannans from spent coffee grounds through sequential microwave superheated water extraction. A maximum 69% mannose recovery was made with the fifth MAE cycle. They also observed that with increasing number of extractions, the average degree of polymerization decreased. Similarly, Pavlović *et al.* (2013)

demonstrated MAE as a rapid, effective and cheap method for the extraction of natural antioxidants from spent filter coffee residues. Maximum total polyphenols were extracted in 40 s microwave treatment using 20% ethanol aqueous solution.

Hiranvarachat and Devahastin (2014) used intermittent microwave radiation to extract carotenoids from carrot peels at different intermittency ratios (α), which was defined as the fraction of the microwave radiation time to the total processing time in one cycle. They observed that at $\alpha = 1/4$, the amounts of extractable β -carotene and total carotenoids were greater than continuous MAE.

Enzyme-assisted extraction

EAE is an extraction technique that uses enzymes such as protease, cellulase, hemicellulase, xylase, α -amylase and β -glucosidase for the extraction of valuable compounds from plant tissues. The other common enzymes used for this purpose are alcalase, polygalacturonase, neurase, pectinesterase and endopolygalacturonase (Jeong *et al.*, 2014; Wikiera *et al.*, 2015a, 2015b; Yuliarti *et al.*, 2015). EAE increases the extraction yield, uses low temperature and lesser energy and gives better product quality with increased yield as compared with traditional extraction processes. The problem of corrosion of equipment observed during high-temperature extraction process gets eliminated through EAE (Roselló-Soto *et al.*, 2016). It can also be combined with the traditional solvent extraction process to reduce solvent and time requirement for extraction. EAE has been used as a pre-treatment process for the extraction using water as a solvent instead of organic chemicals, which makes it an eco-friendly technology.

The EAE technique involves the use of cell-wall-disintegrating enzymes (pectinases and glucanases) that help to weaken or break down the cell wall and increase the cell-wall permeability so that the bioactive compounds present in the cell can be easily extracted. EAE is mainly carried out through two mechanisms: enzyme-assisted aqueous extraction and enzyme-assisted cold-pressing. Enzyme-assisted aqueous extraction is mainly used for oil extraction from seeds. In enzyme-assisted cold-pressing, hydrolyzation of cell wall takes place because of the activity of enzymes. EAE depends on the enzyme used and its concentration, reaction time, pH value, temperature and particle size of the plant matrix to be used (Roselló-Soto *et al.*, 2016). Enzyme response is influenced by some factors such as temperature, percentage of dissolved oxygen and nutrient availability. If these factors are not present at the required level, it acts as a barrier to scale-up the EAE process.

EAE has been used for the extraction of pectin from food waste such as apple pomace (Wikiera *et al.*, 2015a, 2015b), kiwifruit pomace (Yuliarti *et al.*, 2015), passion fruit peel (Liew *et al.*, 2015), lime peel (Dominiak *et al.*, 2014), rapeseed cake (Jeong *et al.*, 2014) and yuzu pomace (Lim *et al.*, 2012). Wikiera *et al.* (2015a) performed pectin extraction from apple pomace by using three different types of enzymes, Cellucast, Econase and Viscoferm. They found that the initial pH and extraction temperature of the reaction mixture has an influence over the pectin yield. A pectin yield of 18.95% and 17.86% was acquired for Cellucast and Viscoferm, respectively, and these yield values are higher than that of the yield (14.52%) obtained after acidic extraction. In their second related study, Wikiera *et al.* (2015b) used Cellucast 1.5L at different doses for fixed time duration, pH and temperature. They found that the acid extraction gives a yield of 8.2%, which was lesser than the yield (10.8%) obtained by the lowest dose of Cellucast 1.5L. Pectin recovery of 15.3% was found at the lowest dose of enzyme. Yuliarti *et al.* (2015) conducted EAE of pectin from kiwifruit pomace with Cellucast 1.5L and followed it up by an acid extraction process. They found that Cellucast 1.5L shows its maximum activity within the temperature range of 50–60°C and pH range of 4.5–6.0. Liew *et al.* (2015) used Cellucast 1.5L for the extraction of pectin from

passion fruit peel. They found that the highest yield (7.12%) of pectin was obtained at a temperature of 61.11°C for an elapsed time of 102 min. [Dominiak et al. \(2014\)](#) used enzymes like Laminex C2K, Validase TRL, Multifect B and GC880 to extract pectin from lime peel and found different yield values for different enzymes. They also reported different extraction yields at different pH values. A pectin yield of 24%–32% was obtained for all the enzymes at pH 4.8. [Jeong et al. \(2014\)](#) found that the highest pectin yield of 6.85% was obtained from rapeseed cake at Celluclast–Alcalase ratio of 1:4. [Lim et al. \(2012\)](#) reported that the highest pectin yield (8%) was obtained after 1 h of extraction at a temperature of 40°C by using Viscozyme.

EAE has been used in the extraction of phenolic compounds from food waste. [Teles et al. \(2021\)](#) used EAE in combination with high hydrostatic pressure (HPP) for extraction of phenolic compounds from grape pomace and observed the concurrent use of both technology as a effective and clean method to recover the high value bioactive compounds from food waste. The pretreatment of enzymes by HPP before extraction resulted in maximum yield. [Xu et al. \(2014\)](#) used enzymes cellulase, pectinase, β -glucosidase for hydrolysis time 1–24 h for the release of phenolic compounds from muscadine grape skin and seed. They observed that although the EAE reduced the extraction time, the yield of phenolic extracted decreased as compared with solvent (50% ethanol) extraction. The antioxidant activity though was enhanced by EAE. [Gómez-García et al. \(2012\)](#) used commercial enzymes such as Celluclast® 1.5 L, Pectinex® Ultra and Novoferm® to extract phenolic compounds from grape (*Vitis vinifera* L.) residues. They observed that the release of phenolic compounds was best facilitated by Novoferm® followed by Pectinex® Ultra and Celluclast® 1.5 L. Similarly, [Fernández et al. \(2015\)](#) used enzymes pectinase, cellulase and tannase to extract proanthocyanidins from the skins and seeds of Pais grapes. They observed that on grape skins, pectinase was most effective for the release of total phenols, while on grape seed, all the three enzymes were effective in increasing the phenolic extraction. [Ferri et al. \(2016\)](#) used EAE for the recovery of polyphenols from red grape pomace (*Vitis vinifera* L.), a winemaking by-product by using commercial form of pectinase, α -amylase, xylanase and cellulose based enzymes. Fungamyl and Celluclast enzymes were found to maximum accelerating effect on release of polyphenol from wet pomace (fresh frozen pomace). Dried pomace yielded lesser polyphenols. [Nishad et al. \(2019\)](#) optimized the condition for the EAE of polyphenols from *Citrus sinensis* (cv. Malta) peel using response surface methodology. The optimized condition for EAE was 0.84% enzyme concentration, 30.94 ml/g solvent solid ratio and 4.87 h extraction time. [Saad et al. \(2019\)](#) used alkaline protease in aqueous medium to extract polyphenols from raspberry pomace. They reported an increase of 48% and 25% in the yields and antioxidant activity, respectively, of polyphenols as compared with extraction using organic solvent.

Supercritical fluid extraction

In SFE, a supercritical fluid is used to extract the bioactive compounds from plant materials. Supercritical fluids have interim physico-chemical properties (viscosity, diffusivity, density, dielectric constant, etc.) between liquid and gases. Above the critical point, the viscosity of the supercritical fluids is low and diffusivity is high. By modifying the temperature and pressure, the physico-chemical properties of supercritical fluids can be tuned. The density of the supercritical fluid can also be modified by changing the temperature and pressure to enhance the solubility of the target compounds. Supercritical fluids have improved transport properties compared with liquids; therefore, they can easily diffuse into solids and give faster rate of extraction ([Cavalcanti et al., 2011](#)).

The substances used as supercritical fluids are CO₂, water, ammonia and hydrocarbons like propane, ethane and fluorinated hydrocarbons. CO₂ is the mostly used compound in SFE because of its low cost, non-toxicity, non-flammability, chemical stability and convenient critical point (73 bar and 31.1°C). In general, CO₂ is nonpolar in nature, but its activity falls in between a weakly polar solvent and a truly nonpolar solvent. As its molecular quadrupole is large, it shows some restricted affinity to polar solutes. Co-solvents, modifiers or entrainers are added during SFE to increase the affinity of CO₂ to a variety of solutes (Ballesteros-Vivas *et al.*, 2019; Varace *et al.*, 2019). CO₂ is synthesized as a by-product of combustion, fermentation and ammonia synthesis. Use of CO₂ in SFE helps to avoid its release in atmosphere and minimize the greenhouse effect. Because of this, SFE is considered as an environment-friendly technology (Cavalcanti *et al.*, 2011). As a solvent-free method, SFE using CO₂ has been used for the extraction of antioxidants, vitamins and amino acids from food waste and food industry by-products.

Most of the studies on SFE of bioactive compounds from food by-products have been carried out using CO₂ as a supercritical fluid and ethanol as a solvent. Limonin and naringin extraction from grapefruit seeds by SFE was performed by Yu *et al.* (2007). The maximum limonin yield (0.6%) was obtained at 50°C, 60 min at 48.3 MPa, while the maximum naringin yield (0.02%) was obtained at 50°C, 40 min at 41.4 MPa.

Phenolic compound extraction from orange pomace was conducted by Espinosa-Pardo *et al.* (2017). SFE required ten times less solvent and 78% less time than the conventional soxhlet extraction. Antioxidants extraction from jabuticaba by-products was conducted by Cavalcanti *et al.* (2011). A temperature of 50°C and a pressure of 20 MPa are considered as efficient conditions for a yield of 15% antioxidants with a minimum manufacturing cost. Nobiletin and tangeretin extraction from orange peel was conducted by Toledo-Guillén *et al.* (2010). A yield of 0.29% nobiletin and 0.02% tangeretin was obtained at a temperature of 60°C and a pressure of 40 MPa. Nobiletin and tangeretin extraction from *Citrus depressa* Hayata peel was conducted by Lee *et al.* (2010). The yield obtained by SFE was 7% higher than the yield obtained by conventional solid-liquid extraction. Total phenolic compounds and total flavonoids extraction from radish leaves was reported by Goyeneche *et al.* (2018). They observed increased yield on increase of temperature from 35°C to 40°C. The phenolic compounds yield obtained by SFE is almost twice the yield obtained by traditional methods of extraction. The maximum yield of flavonoid compounds is obtained at 40°C and 40 MPa. Extraction of phytochemical compounds (total phenolic compounds and total flavonoids) from soybean residue was conducted by Alvarez *et al.* (2019). As a co-solvent, ethanol is used with supercritical CO₂. The highest amount of yield obtained by SFE for both the compounds was 10.5%. This yield was obtained at a temperature of 35°C and a pressure of 40 MPa.

Caffeine extraction from coffee husks and spent coffee grounds was conducted by Andrade *et al.* (2012) to analyse the effect of ethanol as a co-solvent on the extraction yield. They observed better yield at lower pressure when ethanol was used as co-solvent as compared with extraction by CO₂ alone. Similarly, Ferrentino *et al.* (2018) studied the effect of raw material condition and use of ethanol as a co-solvent on the extraction of phenolic compounds from apple pomace. They observed that freeze-dried samples gave better results compared with fresh and oven-dried samples. The use of ethanol also increased the yield for every type of sample. The authors have also concluded that the extraction yield obtained by SFE is much lesser than the yield obtained by the conventional extraction process.

Manna *et al.* (2015) carried out the extraction of triglycerides from waste hazelnut and spent ground coffee as well as polyphenols from seed and skin of grape pomace. They found 60°C and 50 MPa as the suitable temperature and pressure, respectively, for the extraction of triglycerides

from both studied sources and polyphenols from seed of grape pomace. The maximum yield (2.99 ± 0.08 mg GAE/g) of polyphenols from skin fraction of grape pomace is obtained at a temperature of 40°C and a pressure of 20 MPa with a maximum extraction efficiency of 25%, which is far from the efficiency of the conventional soxhlet extraction process.

Pulse electric field extraction

Pulse electric field extraction (PEFE) is a very promising and emerging technique for the extraction of valuable compounds from food waste and by-products by using electric field in terms of pulses. The material to be treated by PEFE is placed between two electrodes. An electric field is generated by the supplied voltage. The intensity of this electric field depends on the supplied voltage and the gap between the two electrodes. When the plant cells are exposed to the electric field, cytoplasmic membranes get damaged and temporary (reversible) or permanent (irreversible) pores are formed. This phenomenon, known as electroporation, increases the permeability of the cell membrane drastically, thereby increasing the ease of extraction (Roselló-Soto *et al.*, 2015). In PEF equipment, the pulse amplitude ranges from 0.1–0.3 to 20–80 kV/cm. PEF treatment is performed for a time duration of less than 1 s (μ s or ms). Moderate electric field (0.5 and 1 kV/cm; for 10^{-4} – 10^{-2} s) leads to damage in the cell membrane with a minimum increase in temperature. Because of this reason, PEF is a suitable process of extraction for heat-sensitive compounds. The electric field strength and the processing time are the two critical processing parameters that help in the characterization of PEF treatment. The processing parameters depend on the specific energy and the number of pulses delivered (Martínez *et al.*, 2018). Because of the destruction of the membrane structure of the plant cell, mass transfer through it is increased, which enhances the extraction of valuable intracellular compounds and also helps to reduce the extraction time.

Generally pulse electric field is used as a pre-treatment to improve the extraction process. A large number of food industries have adopted the PEF equipment to give a pre-treatment to the food matrices and to scale up the extraction process. PEF has some advantages, such as:

- It is a non-thermal process; as a pre-treatment, it enhances the extraction as compared with heat-based pre-treatment.
- Energy requirement is low.
- It does not affect the overall structure of the cell because of the selective extraction of intracellular compounds.

Therefore, the extracts are purer; so there is no need of additional purification steps, leading to a reduction in the the overall operational cost.

Redondo *et al.* (2018) used PEF for extraction of phenolic and flavonoid compounds from peach by-products and reported increase in yield when the electric field strength was increased from zero to 5 kV/cm. At electric field strength of 5 kV/cm, the highest yield for both the phenolic (57.1 mg GAE/100 g) and flavonoid compounds (37.8 mg CE/100 g) at a temperature of 35°C and 80% methanol with a treatment time of 90 μ s was obtained. El Kantar *et al.* (2018) investigated the extraction of polyphenols from orange peels by PEF treatment. They found that the application of high-strength electric field (10 kV/cm) promotes the extraction of polyphenols up to 22 mg GAE/g DM. Extraction of polyphenols and flavonoids from orange peels was reported by Luengo *et al.* (2013). The authors have concluded that as the treatment time and electric field strength increase, the disintegration of cell is also increased. They found that the maximum polyphenol yield was obtained at an electric field strength of 7 kV/cm, while the maximum yield of naringin and hesperidin was

obtained at an electric field strength of 5 kV/cm with treatment time of 60 μ s and a pressing time of 30 min. Anthocyanins and polyphenols extraction from grape pomace was performed by Brianceau *et al.* (2015). The authors have concluded that the highest anthocyanin and polyphenols yield was obtained at a temperature of 35°C and 50°C, respectively. The energy consumption of 18 kJ/kg, electric field strength of 1.2 kV/cm and extraction time of 420 min was the same for both the compounds. Extraction of anthocyanins from fermented grape pomace was conducted by Barba *et al.* (2015) using water as a solvent. The authors have concluded that the total anthocyanin yield in PEF is increased up to 22% and 55% in contrast with the ultrasound and high-voltage electric discharges-assisted extraction. Extraction of polysaccharides, proteins and polyphenols from *Agaricus bisporus* was conducted by Xue and Farid (2015). The researchers have obtained a yield of 98% polysaccharides, 49% proteins and 51% total polyphenols at an optimum condition of 38.4 kV/cm electric field strength, 85°C and 272 μ s treatment time. The yield of polysaccharides, proteins and total polyphenols obtained by PEF treatment was 1.75, 1.09 and 2.04 times of the yield obtained by the conventional extraction process.

Pressurized liquid extraction

Pressurized liquid/solvent extraction (PLE) is an advancement of conventional solvent-based extraction at elevated temperature (50–200°C) and pressure (3–20 MPa) near to the supercritical region. It is known by different names such as pressurized fluid extraction, pressurized solvent extraction, accelerated solvent extraction, enhanced solvent extraction or, sometimes, SFE (Nieto *et al.*, 2010). Pressure and temperature are the two important parameters that help to control solvent diffusion, desorption, and other transport mechanisms (Picó, 2017). The increased temperature enhances the distribution coefficient as well as the solubility of analytes and matrix–analytes interactions. The increased pressure helps in keeping the solvent below its boiling point (liquid state) and allows for higher working temperature. The extraction solvent's physical properties and polarity have a strong influence over the conduction of analytes from the plant matrix. Increased pressure helps in faster penetration of the solvent into the solid matrix. Hence, the elevated temperature and pressure help to increase extraction efficiency. PLE has some advantages over the conventional extraction process such as reduced extraction time, smaller amount of solvents, barrier to sunlight and oxygen, no requirement of extracted compound's filtration and fully automated and ease of operation (Picó, 2017).

The extraction of bioactive compounds using PLE from food waste has been less explored as compared with other techniques. Limited food waste, i.e orange peels (Barrales *et al.*, 2018), grape marc (Pereira *et al.*, 2019), blackberry residues, blueberry residues and grumixama residues (Machado *et al.*, 2017) and jabuticaba skins (Santos *et al.*, 2012), has been explored for the extraction of phenolic compounds and anthocyanins. They have used water, ethanol, ethonal-water and composite solvent (ethyl acetate in methanol) as a solvent. Barrales *et al.* (2018) reported the highest yield of hesperidin and total phenolic compounds from orange peels at 75% ethanol, whereas the Pereira *et al.* (2019) reported the highest yield of phenolic compounds and monomeric anthocyanins from grape marc at 50% (w/w) ethanol-water. Machado *et al.* (2017) reported the highest yield of phenolic compounds and anthocyanin from blackberry residues, blueberry residues and grumixama residues with water as a solvent at a pH value of 2.0 and 70% of ethanol. Santos *et al.* (2012) reported and optimized the extraction of phenolic compounds and anthocyanins from jabuticaba skins and the highest yield was obtained at 99.5% ethanol. They concluded that the recovery of the bioactive compound depends upon the sample matrix and solvent used in addition to pressure and temperature.

Conclusion

The applications of these novel technologies can lead to an increase in the extraction yields of bioactive compounds with decreased extraction temperature and time. These are some important technologies that could be very useful for the extraction of bioactive compounds from different waste parts of food commodities. Moreover, the yield is comparably greater than the conventional process. Among those technologies, EAE, SFE and PEF are very suitable for the extraction of heat-sensitive compounds. MAE is suitable for those compounds that are not considered as heat sensitive and when rapid heating is required. SFE process can be quickly replaced by PLE, because of its limitations to bind with polar analytes. UAE and PLE can damage the cell structure fully, because of which the level of impurities in the end products could be higher. EAE can help to obtain improved yields of pectin compared with other processes. The quality of the end product is better through novel extraction methods than that of the end products extracted conventionally. A hybrid process (combining two such processes) can be adopted for better extraction performance.

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Corresponding author

Vijay Singh Sharanagat can be contacted at: vijaysinghs42@gmail.com