Critical Reviews in Food Science and Nutrition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

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To cite this article: E. J. Rifna, N. N Misra & Madhuresh Dwivedi (2021): Recent advances in extraction technologies for recovery of bioactive compounds derived from fruit and vegetable waste peels: A review, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2021.1952923

To link to this article: https://doi.org/10.1080/10408398.2021.1952923

Published online: 26 Jul 2021.

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2021.1952923

REVIEW

Recent advances in extraction technologies for recovery of bioactive compounds derived from fruit and vegetable waste peels: A review

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ABSTRACT

Fruits and vegetables are the most important commodities of trade value among horticultural produce. They are utilized as raw or processed, owing to the presence of health-promoting components. Significant quantities of waste are produced during fruits and vegetables processing that are majorly accounted by waste peels (∼90–92%). These wastes, however, are usually exceptionally abundant in bioactive molecules. Retrieving these valuable compounds is a core objective for the valorization of waste peel, besides making them a prevailing source of beneficial additives in food and pharmaceutical industry. The current review is focused on extraction of bioactive compounds derived from fruit and vegetable waste peels and highlights the supreme attractive conventional and non-conventional extraction techniques, such as microwave-assisted, ultrasound assisted, pulsed electric fields, pulsed ohmic heating, pressurized liquid extraction, supercritical fluid extraction, pressurized hot water, high hydrostatic pressure, dielectric barrier discharge plasma extraction, enzyme-assisted extraction and the application of "green" solvents say as well as their synergistic effects that have been applied to recover bioactive from waste peels. Superior yields achieved with non-conventional technologies were identified to be of chief interest, considering direct positive economic consequences. This review also emphasizes leveraging efficient, modern extraction technologies for valorizing abundantly available low-cost waste peel, to achieve economical substitutes, whilst safeguarding the environment and building a circular economy. It is supposed that the findings discussed though this review might be a valuable tool for fruit and vegetable processing industry to imply an economical and effectual sustainable extraction methods, converting waste peel by-product to a high added value functional product.

KEYWORDS
Peel waste valorization; extraction; bioactive compounds; antioxidants; non-conventional extraction methods

1. Introduction

Fruits and vegetables are elementary foods for human physical health as they endow with diverse flavors and are related to enhanced quality of life. Beyond their delectable tang and savor, horticultural crops are acknowledged to lessen the risk of numerous chronic diseases. Fruits and vegetables hold considerable levels of phytoconstituents that are negatively related to the transience and morbidity from cardiovascular disease and cerebrovascular accidents (Vilariño, Franco, and Quarrington 2017). Recognizing that fruits and vegetables have a vital role in the human diet, the demand for these horticultural food products has risen very notably. Owing to the boost in consumer's awareness of dietary habits, benefits from intake of fruits and vegetables, and an increase in the world population, the demand for fruits and vegetables has increased considerably. In a report of the Food and Agriculture Organization (FAO), the production of horticultural products for the year 2019 was estimated to be 314.5 million tones, which was about 1% more than the world production of fruit and vegetable (F&V) produced in 2017–2018 (FAOSTAT-FAO statistical database, 2019). China, India, the USA, Turkey, Russia, Vietnam and Mexico produce over 67% of the world's horticultural produce (Paggiola et al. 2016). In most instances, horticultural crops are ingested directly by humans. However, owing to the seasonal accessibility of most fruits and vegetables and their perishable nature, attempts are made to rapidly process the fruits and vegetables to prolong their shelf-life, make them accessible throughout the year as well as in regions where they are not available. In addition, preservation of horticultural produce through processing also maintains their physicochemical attributes and nutritive value. The various forms to which fruits and vegetables are processed in order to extend their shelf-life includes puree, grits, pulp, flakes, powders, etc. (Raks, Al-Suod, and Buszewski 2018).

Over the most recent decade, the food industry has spotted prodigious growth and is one of the fastest expanding sectors throughout the globe. However, considerable aggregate of wastes is produced through the processing. On the reports from food processing industries, about 20–30% of the wastes of the whole waste fraction are produced during the processing of food and drink, its distribution and retail (Nigam and Pandey 2009; Ramachandran et al. 2007). In contrast to the other food processing sector, higher amounts

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of wastes, equivalent to 25–30%, are obtained from fruits and vegetables industry that majorly includes peels (about 90–92%). This data is followed by seeds, core, rag, stones, pods, vine, shell, skin, pomace, etc. (remaining 8–10%) (Rodríguez et al. 2008). Studies reported that waste peels generated through fruit and vegetable processing are to be recognized as specialized residues owing to their high levels of residual bioactive compounds like phenols, tannins and phytochemicals (compared to that isolated from the rest of the byproducts). Henceforth in industrial processing of F&V waste peel was considered as the major waste fraction, disposal of which has been a serious environmental problem. Broadly, there are two approaches to discard F&V peel waste; incineration and landfill (Buzby et al. 2011). Incineration results in consequent development and ejection of pollutants and secondary compounds such as acid gases, furans, while inapt landfill management results in the release of methane and carbon dioxide leading to environmental impacts and health risks (Sindhu et al. 2019). For the reasons discussed so far, there is an urgent need to assess the valorization of these wastes.

One obvious approach to tackle with the issue of F&V wastes would be to exploit the majority of processing by-products for production, extraction, synthesis or preparation of many valuable compounds, thereby supporting production of valuable substances (Hodges, Buzby, and Bennett 2011). Investigations performed on many F&V wastes have revealed that peels, ordinarily considered as waste, hold high percentage of valuable phytoconstituents and bioactive compounds, like antioxidants, phenolic compounds, carotenoids, organic acids, Vitamin C, dietary fiber, enzymes, among others (Vilariño, Franco, and Quarrington 2017). Furthermore, huge amount of soluble dietary fiber gets generated from the by-products of agriculture, particularly during processing of soy pulp, wheat bran, fruits and vegetables. The SDF thus produced is identified to play a vital role in human health as this indigestible cellular constituent of plant matrix have got immense benefits say prevention from cardiovascular diseases, diabetes, colon cancer, and so forth as reported by Li et al. (2020).

The growing knowledge about F&V by-products and their capacity to scavenge free-radicals contributing to activities like antioxidant, antimicrobial, anti-inflammatory and antiproliferative etc. have promoted the use of these bioactive compounds as natural food additives over synthetic antimicrobial and antioxidant agents, which have been linked to carcinogenic and mutagenic effects in humans (Petropoulos, Di Gioia, and Ntatsi 2017).

Another prominent aspect that has specifically led to the drift in trend toward natural products among the consumer for polyphenols includes the increased health awareness among consumers, particularly aged people, and the outset of various cardiac and alkaptonuria related disorders. As per the report published by WSDE (1994) it was studied that proper utilization of waste generated enhances profit, decreases accountability, reduces use of water, as well as builds worthy civic relations. The appropriate usage of peel waste resources attained through horticultural produce might begin an ingenuity for ecological growth to lessen ecological problems as well as to progress human well-being through foods supplemented with health-promoting ingredients Current reports published by Transparency Market Research, a worldwide market intelligence group, indicated that the market for polyphenols from a natural source in 2020 is expected to reach an annual growth rate of 6.1% (Transparency Market Research 2018). In light of the recent rise in demand for herbal polyphenols, a preferable and advantageous proposal is to recover the phytoconstituents present in waste peels through feasible and efficient technologies thus to make it beneficial for biotechnological, pharmaceutical, food and cosmetics industry (Raks, Al-Suod, and Buszewski 2018). Identifying an optimized extraction technique, quantification of isolated extract and determining stability of extract during storage are the major critical processes to retrain bioactivity of isolates from F&V wastes in their pure form. Phytochemically, the above mentioned processes can be described as chief techniques for separation performed for the retrieval and purification of bioactive from F&V peel waste, making them utilitarian in a broad scale of applications. Most of the novel extraction technologies developed are known to be environmentally benign, with reduced energy consumption, low or no use of organic solvent and decreased extraction time (Chemat, Vian, and Cravotto 2012; Szentmihályi et al. 2002). Consequently, novel extraction technologies could lower the overall cost of the products compared to increased extraction period and high energy demand of conventional techniques. Thus, the implementation of novel and efficient extraction technologies relying on a multitude of mechanisms will be rewarding for bioactive extraction from F&V peel waste.

Several recent reviews have discussed the application of extraction technologies for recovering the bioactive compounds from food waste (pomace, unutilized, unconsumed, excess, and spoiled/food waste from domestic and industry waste) (Barba et al. 2016; Soquetta, Terra, and Bastos 2018; Torres-Valenzuela, Ballesteros-Gómez, and Rubio 2019) without noteworthy attention on fruits and vegetable peels that constitute 90% of processing waste in fruit and vegetable industry. A critical review elucidating on the application of pertinent extraction technologies for extraction of bioactives from fruit/vegetable waste peels was also found missing from literature. To fill this gap, this work reviews conventional and novel technologies as well as their combinations for extraction of phytoconstituents and bioactives from fruit/vegetable waste peels. The review also analyses the underlying mechanisms of extraction and addresses the identification and quantification aspects of the bioactive compounds. Further, discussions about thermal stability of extracts and elucidation of their potential uses in pharmaceutical and food applications are also included.

2. Bioactive in waste peel – volume and significance

Numerous studies have focused on estimation of a variety of bioactive in fruit and vegetable peel (Ben-Othman, Jõudu, and Bhat 2020; Deo and Sakhale 2018; Singh et al. 2016).

These have unanimously supported the presence of bioactive compounds in quantities that could support commercialization. These studies have also emphasized that the targeted bioactive could have several applications in food, pharmaceuticals, and chemical industry, besides minimizing environmental impacts, and supporting sustainability goals (Ali et al. 2016; Sepelev and Galoburda 2015; Vu, Scarlett, and Vuong 2018)

Literature suggests that F&V processing generates a wide array of by-products (traditionally considered as waste), of which, waste peel contributes about 15–60% (Jayathilakan et al. 2012). The largest producers of F&V peel wastes are Philippines, China, India and the USA (Saini, Panesar, and Bera 2019). As peel is not deployed for any profit-oriented purpose it is generally disposed-off as waste, constituting an environmental nuisance. Several investigations have elucidated the composition and identified means for efficient utilization of waste peels (Bernal-Vicente et al. 2008; Grassino et al. 2016; Oberleitner et al. 2017). It was estimated that around 55 MMT (Metric Million Tonnes) waste peel is released from a fruit or vegetable processing industry, which includes primary processing of F&Vs (5.5 MMT), during canning as well as freezing (6 MMT), at wineries (5–9 MMT), among others.

The phenolic content in many fruit peels (papaya, passion fruit, pomegranate) is known to be about two times higher than available in seed and pulp. Despite the intra-varietal differences, in papaya peel the mineral composition, Vitamin C and antioxidant activity has been revealed to be higher than present in seeds. Likewise, Sultana et al. (2012) observed that gallotannins and total phenolic content in most tropical fruits (mango, mangosteeen, dragon fruit) was significantly higher in peels when compared to pulp, stone and kernel. Presence of 17.74–18.63% of pectin in exotic fruit peels (jackfruit and banana) make it applicable in the preparation of biodegradable films and bio sorbents (Lim et al. 2015; Palacios-Ponce et al. 2017). Wolfe, Wu, and Liu (2003) estimated the antioxidant activity and phytochemical content in flesh and peel of stone fruits (apples) and demonstrated that flavonoids and phenolic percentage were higher in peels than in fruit flesh. Gunwantrao et al. (2016) attempted to extract, bromelain, lutein, α-carotene from citrus fruits peel waste using methanol and ethanol solvents. Results revealed that pineapple and orange waste peels could be applied as antimicrobial agents for safeguarding from chosen pathogens (*Pseudomonas aeruginosa*, *Klebsiella pneumonia* and *Bacillus subtillis*). Numerous scientific studies reported that as with fruits, bioactives in vegetable peel are also significantly higher than in edible parts. The processing of vegetables say; tomato and eggplant produces waste in form of peels and seed in a ratio 60–40%. Therefore, the recommended effective solution to manage the vegetable peel waste is extraction of active molecules, say lycopene from tomato peel, and high quality protein, pigment, fiber, carotenoids and organic acids from others.

Polyphenols and betalain extracted from peels of root vegetables (carrot, beetroot) are valuable as antioxidants (Chhikara et al. 2019; Ravichandran et al. 2013). Cartea et al. (2010) identified that the bioactive compounds present in cruciferous vegetables (broccoli, cauliflower) include phenolic component, flavonoids (namely quercetin and kaempferol), vitamin C and total dietary fiber. Being a rich source of bioactive compound, cauliflower by-product has found applications in nutraceutical products. As per a 2017 report, production of potato accounts to about 3820.00 MMT and it has been estimated that one-third of its whole weight is constituted of waste peel (FAO 2017). In a study, potato peel extract obtained after lyophilization was confirmed for its effective antioxidant activity in various in-vitro systems (Al-Weshahy et al. 2013). Rajasree et al. (2016) observed lipid peroxide inhibition property of waste peel obtained from cucurbitaceae family due to the presence of phenolic and flavonoid compounds. Figure 1 represents the novel extraction technologies and major bioactive compounds extracted from fruit and vegetable peel waste. These works reported that significant concentration of bioactive compounds/phytochemicals and nutrients are present in waste peel and interestingly the biomolecules isolated often possess pharmacological activities like antioxidant, antiproliferative, antimicrobial and anti-inflammatory properties, with antioxidant property being the major.

Recently synthetic chemical compounds have been extensively incorporated into food as antioxidants and antimicrobial agents with the disquiets over safety of usage warranting the need of natural compounds over these man-made compounds. These demands of the consumers to identify and propose natural sources of antioxidant, antiproliferative, antimicrobial and anti-inflammatory agents open the door for the effectual use of bioactives from fruit and vegetable waste peel as alternatives to synthetic antioxidant agents with potential applications in the food and pharmaceutical industry. Henceforth, owing to all aforementioned reasons the bioactive molecule contained in F&V waste peels have been extracted using a gamut of techniques, that for convenience can be segregated into two chief categories: conventional and novel/modern. However, it is worth noting that all the techniques falling into conventional as well as novel have a few general objectives; (a) to extract the desired bioactives without altering their properties, (b) to lower the energy consumption, (c) to obtain extract in the most stable and pure form, (d) to enhance yield of the desired compounds, (e) to act as a robust technique not dependent on variations in the sample matrix, and (f) to offer affordable and environmental friendly extraction technique.

3. Conventional extraction techniques

3.1. Soxhlet, maceration, decoction, infusion and percolation

Bioactive molecules or compound known to be present in various F&V wastes have been attempted for extraction using various classical or conventional techniques. Majority of these rely on solvent type used, extraction power of solvent and the use of agitation and temperature. The major conventional technique for obtaining bioactive compounds

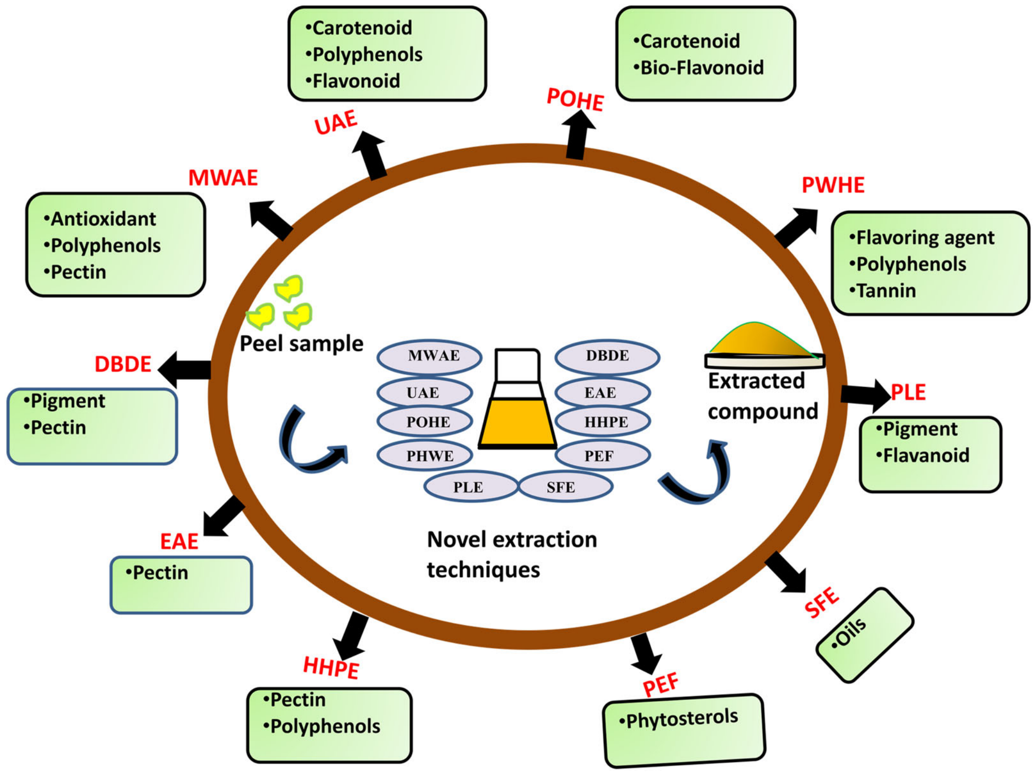

Figure 1. Novel technologies applied for extraction of bioactive compounds from fruit and vegetable waste peel and the class of compound extracted with maximum purity and yield under each technology.

from waste peel includes Soxhlet extraction, maceration, decoction, infusion and percolation. The technique of Soxhlet extraction was originally designed by Fraiz Ritter Von Soxhlet to extract lipid/fat (but did not remain confined to it) (Soxhlet 1879). Later maceration found its use in extraction of bioactive compounds from waste peel owing to its advantage of applicability to thermolabile compounds (Zhang, Lin, and Ye 2018). To improve the efficacy of prevailing conventional extraction techniques, infusion and decoction extractive techniques that follow same principle as maceration have been developed (Handa et al. 2008). Percolation is another method and was reported to be more efficient than maceration as it is a continuous process in which the saturated solvent is persistently being restored by freshly prepared solvent. In particular, the section below outlines the application of conventional technologies for bioactive compound extraction present in waste peel, reveals the ideal storage condition, and analyses thermal stability of extracts. The important studies summarizing the effect of conventional extraction techniques on the recovery of high value-added bioactive compounds from F&V waste peels are summarized in Table 1.

3.1.1. Application of Soxhlet, maceration, decoction, infusion and percolation techniques for extraction of bioactive compounds from fruit and vegetable waste peel

Kodal and Aksu (2001) studied the extraction of carotenoid pigment from orange peel by technique of Soxhlet extraction. Authors reported that, treatment of frozen peel at 79 °C with ethanol at liquid to solid ratio of 40:1, yielded the maximum carotene pigment in the range 4.5 mg carotene/g dry peel. However, the extract was found to easily decompose to its terpene monomer units owing to lipid oxidation. Recently, comparison of conventional (Soxhlet) and non-conventional (microwave, ultrasound and ohmic) extraction methods to recover phenolics from grape peel was performed by Caldas et al. (2018). Of the extracted molecules (catechin, rutin and epicatechin), those isolated by Soxhlet method possessed higher yield (conventional: ∼ 80 mg Gallic Acid Equivalence (GAE)/g; non-conventional: ∼ 65 mg GAE/g). However, purity was significantly higher for extract obtained through non-conventional technique employed compared to conventional method. In general, from the two studies available till date on application of Soxhlet technique on waste peel, it can be clearly concluded that Soxhlet preferable for higher yield of polyphenolic compounds.

To overcome the significant limitation of Soxhlet extraction technique, investigation has been carried out to extract flavonoids (glycosides) from kinnow peels using maceration technique at solute to solvent ratio of 1:10 and extraction temperature of 30 °C (Safdar et al. 2017). It was revealed that maceration technique with 80% ethanol, 50% ethanol and 10% ethyl acetate yielded 18.46%, 15.64% and 5.12%, respectively. Such variations in extraction yield could be attributed to the difference in polarity of the solvents. However, earlier works conducted by Sultana et al. (2008) on extraction of flavonoid compounds from various citrus peel revealed the use of methanol in maceration technique to be most efficient in terms of yield and purity. Therefore, extraction of flavonoid glycosides from kinnow peels using

Table 1. Results published on the application of conventional technologies for extraction of bioactive compounds from fruit and vegetable waste peel.

Extraction technique	Peel matrix	Extracted compound	Treatment condition	Salient results	Reference
Soxhlet extraction	Grape peel	Catechin, rutin and epicatechin	Extraction temperature at 85 °C using ethanol at liquid: solid ratio of 1:10 for 80 min	Soxhlet: 80 mg GAE/g (less stable extract); non-conventional: 65 mg GAE/g (highly stable extract)	(Caldas et al. 2018)
Maceration	Kinnow peels	Flavonoids (glycosides)	Ethanol and ethyl acetate was used at 30 °C for 8–10 h.	80% ethanol, 50% ethanol and 10% ethyl acetate yielded 18.46%, 15.64% and 5.12% of glycosides	(Safdar et al. 2017)
	Mango peel	Polyphenols and flavonoids	Ethanol and methanol solvent at concentration 50, 80 and 100% and solute: solvent ratio 1:20	Solvent concentration level of 80% was more effectual than 50% or 100%	(Safdar et al. 2017)
Decoction	Pomegranate peels	Total phenolic content	100 °C for 10 min	TPC varied between 148 to 237 mg gallic acid equivalent (GAE)/g (DW), with radical-scavenging ability (RSA) falling between 307 to 472 mg ascorbic acid equivalent (AAE)/ g DW	(Turrini et al. 2020)
Infusion	Pomegranate peel	Total Phenolic Content and Total Flavonoid Content	70 °C for 60 min	The band of gallic acid and hydrolyzable tannin in the extracts was confirmed	(Ghosh et al. 2019)
Percolation	Sweet orange peel	Total phenolic content	Methanol, ethanol and distilled water at 3 mL/min for 24 h	Methanol was studied as the effective extraction solvent resulting in the highest extraction yield (28%)	(Thakur, George, and Chakraborty 2020)

methanol solvent and maceration technique could be explored for higher yields.

Romero-Cascales et al. (2005) observed that maceration process using methanol at a temperature of 25 °C yielded highest amount of anthocyanin pigment (300 mg/g) from grape skin. However no stability study was performed for the extract recovered in above work. Zheng et al. (2011) reported that maceration extraction for about 14 h and filtration with 0.45 µm filter yielded about 16.64% of grape peel anthocyanin with acceptable purity and stability of three days under room condition storage. The effects of cold storage of anthocyanin extracts and optimization of time and temperature of holding with regards to stability warrants further studies. In addition Safdar, Kausar, and Nadeem (2017) compared the effect of ultrasound assisted extraction (UAE) and maceration technique to extract the polyphenols and flavonoids from mango peel. Authors reported that extracting with maceration possessed comparatively higher extraction yield at all concentration levels (50%, 80% and 100%) compared to UAE. In general, maceration can be concluded as an effective and easy technique for extraction of bioactive compounds, mainly flavonoids and polyphenols from fruit peel compared to Soxhlet technique.

Rakholiya et al. (2013) studied the effect of decoction extraction method at 100 °C for 30 min to extract antimicrobials from ripe and unripe mango peel. The extracts obtained showed high activity against *S. albus, S. aureus, M. flavus* and possessed zero activity against *B. megaterium* and *L. monocytogenes*. From above study it can also be inferred that, decoction technique is highly suitable for extracting heat stable molecules. Furthermore, this extraction technique also results in extracts containing oil-soluble antimicrobial compound from waste peel compared to Soxhlet and maceration.

Infusion extraction techniques have been widely employed at industrial level chiefly for extracting polyphenols from tea residue waste (Almajano et al. 2008; Pasrija and Anandharamakrishnan 2015). Xu et al. (2008) performed extraction of polyphenols from citrus peel extract using infusion technique (70 °C for 30 min and 100 °C for 60 min). Furthermore, it was also reported that green tea extract possessed a prooxidant effect on marine oils oxidation when investigated examined underneath oven environments at temperatures above 60 °C, and which was owing to the existence of chlorophyll molecule. However, it can be studied that application of infusion extraction for potential in food formulations warrants future research. In case of mangosteen fruit peels, continuous percolation and Soxhlet extraction with 95% ethanol has been carried out at room temperature for 20 h (Pothitirat et al. 2010). Results revealed that Soxhlet extraction exhibited high extraction yield for total phenols, total tannin, α-mangostin, DPPH-scavenging activity and antibacterial property. In general, percolation proves to be an efficient technique compared to maceration owing to its continuous process nature. That said, the challenge arises from the low yield rate and long extraction time and decreased extract purity.

4. Novel extraction techniques

The conventional solvent techniques discussed so far have been employed (and continue to be), for more than a century for extraction of bioactives from plant materials. Nevertheless, the drawbacks associated with conventional technologies make their application relatively unsustainable and/or uneconomical. This is owing to several reasons, including the lower purity of extracts, large extraction periods, low extraction yields, degradation of thermo-sensitive molecules, application of high cost solvents, polluting nature of solvents, and the rising concern about their human safety (Chemat, Rombaut, Meullemiestre, et al. 2017; Cravotto, Binello, and Orio 2011). These major limitations and increased interest of obtaining high-purity peel extract for food and pharmaceutical applications stimulated the need for research that facilitate further cost-effectiveness and greener extractive methods for the extraction of bioactive compounds from a broad array of F&V waste peels (Gorinstein et al. 2001). Currently, novel techniques are attracting progressive interest by various food processing industries owing to their potential to feasibly retrieve value-added components with reduced energy consumption, without resorting to conventional heat-based processing techniques. These technologies are also called as cold extraction processes as they are typically carried out at low temperatures. Azmir et al. (2013) and Chemat et al. (2020) stated that the goal of these novel extraction techniques is to attain a higher rate of extraction by reducing processing steps, achieve enhanced heat and mass transfer, efficient use of energy and reduced size of equipment. The use of these processes is also proposed to safeguard the natural resources and surrounding environment and most importantly the economy of the targeted compounds (maximizing the inclusion of bioactive compounds of the waste peel in the final extract) (Da Silva, Rocha-Santos, and Duarte 2016). The extensively promising novel techniques for extraction and isolation of bioactive compounds appears to be microwave assisted extraction (MWAE), ultrasound assisted extraction (UAE), pressurized hot water extraction (PHWE), pressurized liquid extraction (PLE), pulsed electric field assisted extraction (PEFAE), pulsed ohmic heated assisted extraction (POHE), enzyme assisted extraction (EAE), dielectric barrier discharge plasma extraction (DBDE), and high hydrostatic pressure assisted extraction (HHPE) of which most have got established, and few like pulsed ohmic extraction and high pressure extraction are on the verge of commercialization. The important works summarizing the effect of non-conventional extraction techniques on the recovery of high value-added bioactive compounds from F&V waste peels are summarized in Table 2.

4.1. Microwave assisted extraction (MWAE)

Microwave consists of two oscillating perpendicular fields: magnetic field and electric field and falls in frequency range from 300 MHz to 300 GHz. Microwave assisted extraction (MWAE) is an efficient and rapid method involving extraction of bioactive constituents from plant matrices and their by-products. The microwave heating processes rely on the direct effects of oscillating electromagnetic fields on polar molecules (Abdel-Aal et al. 2014; Chemat 2012). A number of works were initially conducted to determine the efficacy of microwave assisted extraction technique for extraction of bioactives from waste peels for food applications. They revealed the efficacy to be a function of following parameters: microwave power, time of extraction, peel matrix, matrix particle size, stirring effect, sample moisture content, solvent selected and organic solvent additives used. In addition, MWAE has also been demonstrated to be a selective process to extract bioactive and organic constituents that are highly intact with a better recovery than conventional extraction techniques. In addition, microwave application has been reported to be efficient in inactivating enzymes present in foods, seed germination, maintaining organoleptic properties, product forming, product reformation, clarification and chiefly for microbial inactivation (Ekezie et al. 2017; Rifna and Dwivedi 2021; Rifna, Ramanan, and Mahendran 2019; Rifna et al. 2019). However, as will be observed later in this review, microwave assisted extraction treatment turns out to be an important technique for extraction with higher yield from F&V peels.

4.1.1. Mechanism of MWAE from waste peel

Fruit and vegetable waste peels after pre-extraction processes (drying and/or size reduction) hold microscopic moisture fractions acting as targets for microwave heating. Owing to the interaction of microwave radiation with bound water in the peel sample, pressure and temperature accumulates inside the plant cells. A schematic diagram of microwave assisted extraction system is shown in Figure 2. The MWAE process consists of several steps in order to achieve efficient extraction of phytochemicals from waste peels (Delazar et al. 2012). It begins with the production of electromagnetic (EM) waves that separates the targeted compound from peel sample matrix owing to enhanced pressure and temperature. Subsequently, bioactive cellular components present inside the waste peel interact with the waves holding photonic energy and results in the heating of the bound moisture confined within the peel matrix. The pressure developed inside the peel at cellular level leads to rapid swelling and rupturing of cellular components thus facilitating diffusion of the selected solvent into the peel matrix. All this process eventually promotes leaching of targeted phytochemical solutes from the waste peel matrix. It was also identified that as the EM wave starts to generate during the MWAE process the chelation of metal ions existing within polyphenols or flavonoid complex in peel matrix gets initiated. The capability of polyphenols or flavonoids to chelate metal cations when exposed to microwaves inhibits the oxidation process and imparts the antioxidant activity to the extract. The possibility of applying MWAE technique to industrial level have proven to be efficient processes for novel extraction of valuable bioactive compounds from natural plant matrices and their by-products generated after processing (Asghari, Ondruschka, and Mazaheritehrani 2011; Chiremba, Rooney, and Beta 2012; Pan, Niu, and Liu 2003).

Table 2. Results published on the application of green technologies for extraction of bioactive compounds from fruit and vegetable waste peel.

Extraction technique	Peel matrix	Extracted compound	Treatment condition	Salient results	Reference
MWAE	Banana peel	FRAP, phenolic compounds, and DPPH	960 W, S/F ratio of 2:100 g/ml and deionized water as solvent	FRAP, phenolic compounds, and DPPH were 95.52 mg TE/g DM; 53.76 mg GAE/g DM; and 95.29 mg TE/g DM	(Vu, Scarlett, and Vuong 2019)
	Mango peel	Pectin	500 W, S/F ratio of (50:50 v/v) with solvent acetone and water	Six times more extract yield at a 30-fold reduced extraction time	(Sommano et al. 2018)
	Carob fruit peel	Total phenolics and antioxidant activity	80 °C, 35% ethanol, 29.5 min, solute:solvent 35 ml/g	Compared to conventional extraction the enhancement achieved for total polyphenols and antimicrobial activity was around 20% 60%, respectively	(Quiles-Carrillo et al. 2019)
	Opuntiaficus-indica fruits	Betalain	70 °C for 1 h	Betalain molecules extracted possessed significant stabilizing effect, preserving the stability (extract color and purity)	(Ciriminna et al. 2019)
UAE	Eggplant peel	TPC and TMA	69.4 °C for 57.5 min at 33.88 kHz	Maximum yield of 2410.71 mg cyanindin-3-glucoside/kg of TMA and TPC of 29.63 g GAE/100 g was achieved	(Dranca and Oroian 2016)
	Purple eggplant peel	Carotenoid	60 °C for 60 min	Cyanidin-3-rutinosideand malvidin-3-rutinoside-5-glucoside were isolated for the first time from eggplant peel waste extract	(Ferarsa et al. 2018)
	Gogi berry peel	Gallic acid	55 °C for 25 min	Extract with highest phenolic content maltodextrin (2%) possessed greatest stability with antibacterial and antifungal activity	(Skenderidis et al. 2019)
	Pomegranate peels	Ellagic acid, gallic acid and punicalin	80 °C for 25 min	Ellagic acid (12.54 mg/g DW); gallic acid (3.58 mg/g DW) and punicalin (65.67 mg/g DW)	(Živković et al. 2018)
	Gac fruit peels	Carotenoid (CY) & antioxidant activity (AA)	200 W for 80 min and 120 W for 25 min	Yielded AA: 820 μmol/L TE/100 g DW; CY: 268 mg/100 g DW	(Chuyen et al. 2018)
	Citrus peels	Flavanoid	70 °C; power 600 W/cm^2 for 10 min	High antiproliferative activity was identified for UAE flavonoid extarct	(Wang et al. 2016)
PHWE	Grape peel	Anthocyanin and tannin	50–200 °C, at 8.00–14.99 MPa), for 5–30 min	Under optimized conditions (100 °C, 10.34 MPa) the anthocyanin and tannin was completely recovered (~98–100%)	(Vergara-Salinas, Cuevas-Valenzuela, and Pérez-Correa 2015)
	Grape skin	Total polyphenols (TP)	80, 100 and 120 °C at 10 MPa for 5 min	TP increased significantly from 44.3 ± 0.4 to 77 ± 3 mg/g with temperature rise from 80 to 120 °C	(Duba et al. 2015)
PLE	Blackberry peel	Total phenolics (TP) and anthocyanin (AA)	140 °C using acidified water as solvent	140 °C yielded maximum TP (7.36 mg GAE/g) and AA (76.03 µmol TE/g) with purity of 91% and 90%	(Machado et al. 2015)
	Citrus peel	Phenolic compounds and reducing sugars	140 °C with ethanol/water at 70% as solvent	Yielded reducing sugars and phenolic compounds two-fold	(Barrales et al. 2018)

(*continued*)

Table 2. Continued.

Extraction technique	Peel matrix	Extracted compound	Treatment condition	Salient results	Reference
				and five-fold better with significant purity	
SFE	Citrus peels	Oleoresin	50 °C, at 20 MPa	Oleoresin extracted from these citrus peels contained limonoids, polymethoxyflavones and phytosterols	(Chen and Huang 2016)
	Citrus peels	Oil recovery	45 and 60 °C at 200 and 250 bars	Oxidative stability was observed to be less in SFE-CO_2 extract compared to soxhlet	(Ndayishimiye, Getachew, and Chun 2017)
	Carrot peels	Carotenoid	59 °C, at 349 bar with ethanol as solvent	Carotenoid recovery was (86.1%) with 97% purity	(de Andrade Lima, Charalampopoulos, and Chatzifragkou 2018)
PEF	Mango peel	Antioxidants rich phenolics	13.3 kW/cm, 60 °C, 1000 kJ/kg	Mangiferin, quercetin, ellagic acid was extracted with high clarity and colloidal stability	(Parniakov et al. 2016)
	Citrus waste peel	Polyphenol	3 kV/cm to 10 kV/cm	Treatment at 10 kV/cm increased the recovery of polyphenols from 16 mg/g DM to 22 mg/g DM for orange and	(El Kantar et al. 2018)
	Red prickly pear	Betanin pigment	20 kV/cm, for 50 min at 20 °C	Maximum betanin yield of 50 mg betanin/100 g peel was obtained	(Koubaa et al. 2016)
	Potato peels	Alkaloids	0.75 kV/cm and 600 μs	PEF treatment yielded 99.9% higher alkaloids than that of the untreated peels	(Hossain et al. 2015)
POHE	Tomato peel	Rutin, carotenoids and lycopene	4, 6,11 kV/cm at 70 °C for 15 min with 70% ethanol	Enhanced the rutin and polyphenol recovery by 77% and 58% more compared to control sample	(Coelho et al. 2019)
	Tomato peels	Polyphenols	40 °C – 70 °C, 15 min using 70% of ethanol	Yielded total phenol of 2.550 ± 0.072 mg gallic acid equivalents/g with a energetic efficiency >90 %	(Coelho et al. 2017)
	Colored potato peels	Phytochemical molecule	15–30 V/cm, for 60–90 °C for 0–10 min	Recovered anthocyanins and phenolic compounds efficiently with energetic efficiency >95 %	(Pereira et al. 2016)
HHPE	Tomato peel	Carotenoids	700 MPa for 10 min	Resulted in six-fold increase in caroteoid compared to solvent extraction process	(Strati, Gogou, and Oreopoulou 2015)
	Tomato peel	Lycopene	500 MPa for 12 min	HHPE causes fissures in tissue resulting in higher release of lycopene	(Xi 2006)
	Potato waste peel	Pectin	200 MPa for 5 min	HPPE extracted pectin with improved emulsifying properties	(Xie et al. 2018)
EAE	Potato peel	Rhamnogalacturonan –1, Galactose	Using pectinase (181 units)	90% RG-1, 72% Galactose content	(Khodaei et al. 2016)
	Apple peel	Pectin	Using celluclast, econase and viscoferm enzyme	Yielded 19% (celluclast), 18% (viscoferm), 12% (econase)	(Wikiera et al. 2015)
	Kiwifruit peel	Pectin	Using celluclast (165 units)	Yielded about 4.5 % w/w pectin compared to 3.6% w/w obtained using acid water extraction	(Muñoz-Almagro et al. 2017)
	Apple peel	Pectin	25–70 µL of Celluclast	15.3% of pectin recovered	(Wikiera, Mika, and Grabacka 2015)
DBDE	Pokan peel	Pectin	pH 2, 40 V, S/L 1:30 for 5.5 min	Yielded only 27% of pectin	(S. 2018)

MWAE: microwave assisted extraction; UAE: ultrasound assisted extraction; PHWE: Pressurized hot water extraction; PLE: pressurized liquid extraction; PEF: pulsed electric field assisted extraction; POHE: pulsed ohmic heated assisted extraction; HHPE: high hydrostatic pressure assisted extraction, EAE: enzyme assisted extraction, DBDE: dielectric barrier discharge plasma extraction.

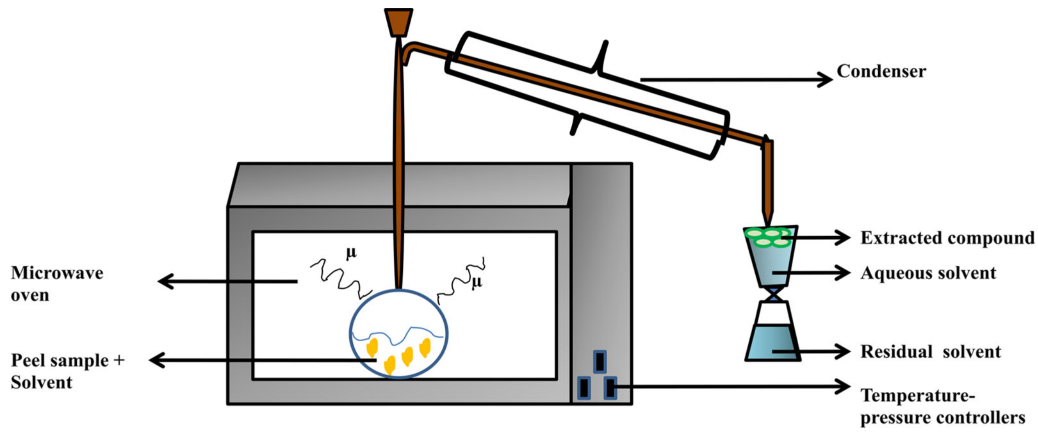

Figure 2. Schematic diagram of microwave assisted extraction system.

4.1.2. MWAE applications for the novel extraction of bioactive compounds from waste peel

The key advantage of MWAE is a rapid and efficient processing. For example, the extraction of phenolic compounds from banana peel was achieved in 6 min by MWAE (960 W, an S/F ratio of 2:100 g/mL) and was found to be much efficient vis-à-vis Soxhlet extraction for 9 to 10 h (Vu, Scarlett, and Vuong 2019). Sommano et al. (2018) compared conventional extraction with phase control microwave assisted extraction (PCMAE) at 500 W for pectin extraction from mango peel. Authors reported about six times more extract yield (10.45% (w/w)) at a 30-fold reduced extraction time in the extract was obtained by PCMAE when compared with the conventional extraction. Likewise, the potential of MWAE to improve the total phenolic content recovery and antioxidant activity from carob fruit skin was evaluated by Quiles-Carrillo et al. (2019). It was observed that microwave assisted extraction (80 °C, 39% ethanol, 29.5 min, 35 mL/g optimized using RSM with R^2 value of 0.69) led to about 33.6 ± 0.4 mg GAE/g yield of polyphenols. In addition, the enhancement achieved by MWAE for total polyphenols was around 20% and 100% and antimicrobial activity was 20% and 60%, when compared to conventional extraction and UAE respectively. It is worth mentioning that all three approaches did not explore the stability of the extracted compounds, which is considered important to preserve extract activity.

Ciriminna et al. (2019) used MWAE (1 h at 70 °C) to get pure extracts of betalain (a polyphenolic pigment) from the peel of *Opuntiaficus-indica* fruits. Authors demonstrated that the preservation of identified polyphenolic molecules after MWAE possessed significant stabilizing effect, preserving the stability (regards to both extract color and purity) of targeted compound. Thus, it can be concluded that this research opened up an effective solution to tackle the betalain pigment chemical instability issue which till date was the cause restricting its broad scale industrial application. Similarly, Liazid et al. (2011) applied MWAE to extract anthocyanin pigment from grape peels and observed that anthocyanin extract was more stable at temperature 100 °C, while above 100 °C the extract stability and yield decreased indicating the compound degradation. In general, MWAE technique can be concluded as an efficient novel technology for highest recovery level of phenolic compounds (especially phenolic pigments). In general MWAE method has numerous merits say rapid heating, decreased thermal gradient, enhanced extraction yield with low solvent volume. This method of extraction could also extract the desired molecule more effectually with greater compound recovery value. Nevertheless, the probable drawback of exposing to microwave energy is that application of increased MW power above a threshold value could lead to significant loses of few bioactive molecules in peels owing to enzymatic and thermal reactions of oxidation. Furthermore, there exist few other major drawback say increased technical difficulty, initial installation charge as well as safety protocols owing to the application of electromagnetic waves. Additionally, there is lower regulation upon the input energy warranting a cautious optimization of microwave process parameters. However, more works targeting to elucidate antimicrobial properties and free radical scavenging activity of waste peel extracts obtained after MWAE can be strongly recommended for future direction as the F&V peels have been revealed to be rich source of nutraceutical and pharmaceutical activities.

4.2. Ultrasound assisted extraction (UAE)

Ultrasound assisted extraction (UAE) process encompasses sound intensity of 5–1000 W/cm^2 and sonication waves falling in frequency range greater than 20 kHz (Soria and Villamiel 2010). UAE has evolved as an assuring method that attains the demanded benchmark as an economical novel extraction technique. Ultrasound has been applied to extract various biomaterials and macromolecules from natural plant source and their by-products. The advantage of UAE system to be easily attached with an already developed system makes its application wider (Patist and Bates 2008). Furthermore, ease to use, flexibility, decreased residence time, noise reduction, safety, quickness, versatility, environmental friendly nature, low solvent usage, reduced emulsifier consumption, its potency to extract heat labile compounds and its low investment during installation and operation are the other remarkable UAE attributes compared to traditional extraction techniques (Chemat, Rombaut, Sicaire, et al. 2017; Shah, Sharma, and Gupta 2005). However, the efficacy of

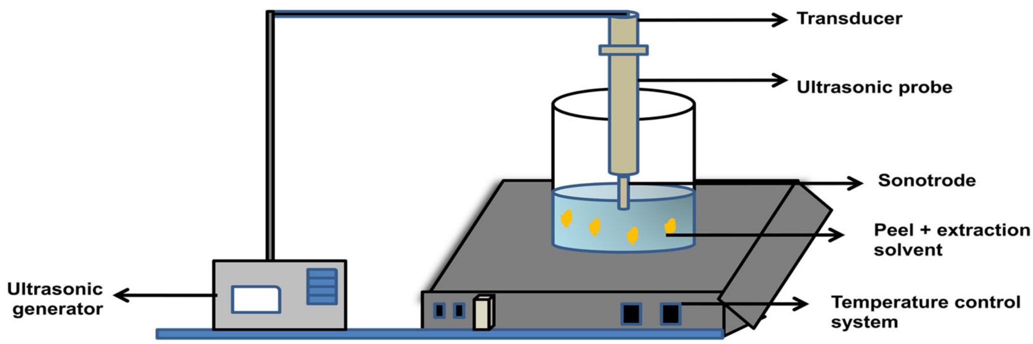

Figure 3. Schematic diagram of ultrasound assisted extraction system.

UAE for extraction of bioactive compounds from waste peel matrices depends on several critical factors – sonication temperature, power pressure, frequency, duty cycle, size of peel sample and pretreatment of peel matrix.

4.2.1. Mechanism of UAE for extraction of targeted compounds from waste peel

The ultrasound frequency range generally used for extraction from plant matrix falls in the range between 20 to 100 kHz. A schematic diagram of ultrasound assisted extraction system is shown in Figure 3. It has been described that when peel matrix after drying and/or grinding is subjected to high frequency ultrasound waves, bubbles get developed in the solvent containing peel sample (Žlabur et al. 2016). The formed bubbles pursue to develop and at further absorption of energy by bubbles it collapses (the process is known as cavitation). Owing to this cavitation process, a large amount of energy is released which abruptly increases the process temperature and pressure resulting in rapid leaching of targeted bioactive compound from waste peel (Vázquez et al. 2014). Moreover, the fruit and vegetable waste peels extracts comprise of substantial amounts of phenolic acid, ascorbic acid and flavonoids. It was observed that during sonication process owing to the cavitation effect produced, the hydroxyl group present in these compounds gets detached eliminating free radicals from them and imparting antioxidant activity to the final peel extract. Thus the commercialization of ultrasound assisted processes has been demonstrated in literature for the revival of valuable compounds from apple pulp, sugarcane, corn shell, watercress, mint leaves, ginger and winery waste revealing significant results as a robust, quick and sustainable substitute to traditional extraction techniques (Asfaram et al. 2018; Raghavi et al. 2016; Rajha et al. 2015; Sindhu et al. 2013; Žlabur et al. 2016). Ultrasound assisted extraction technique has also been applied for the revival of valuable molecules from F&V peel waste; the main studies are reviewed below.

4.2.2. UAE applications for the novel extraction of bioactive compounds from waste peel

Dranca and Oroian (2016) performed UAE for extracting total phenolic content (TPC) and total monomeric anthocyanin (TMA) from eggplant peel. The results described that for obtaining maximum yield of TMA (2410.71 mg/kg) and TPC (29.63 g GAE/100 g) the optimal condition were 33.88 kHz, 76.6% methanol, at 69.4 °C for 57.5 min; and 37 kHz, 54.4% methanol at 55.1 °C for 44.85 min respectively. Ferarsa et al. (2018) conducted UAE in purple eggplant peel for extraction of phenolic compound and reported 60 °C for 60 min at pH 2.0 to be the optimal condition for highest carotenoid yield. Recently, Skenderidis et al. (2019) identified UAE extraction at 55 °C for 25 min at 220 W/cm^2 to be the optimal condition for gallic acid extraction from gogi berry peel possessing significant antibacterial and little antifungal activity. Another study was intended to describe the effect of UAE on phenolic extraction from pomegranate peels (Živković et al. 2018). For maximum extraction of targeted polyphenols say: ellagic acid (12.54 mg/g DW); gallic acid (3.58 mg/g DW) and punicalagin (65.67 mg/g DW) from waste peel the optimal condition was identified to be extraction temperature of 80 °C for 25 min using 59% ethanol as the solvent. The effect of UAE parameter on the yield of phenolic compounds from citrus peel was investigated by Ma et al. (2009) and was compared to yield obtained through maceration process. The study showed that UAE at 15 °C for 1 h yielded 31.72, 763.54 and 29.99 mg/g of caffeic, ferulic, vanillic acids compared to 12.46 to, 189.99 to, 19.23 mg/g obtained using conventional maceration process at process temperature of 40 °C for 8 h. In a work conducted by Londoño-Londoño et al. (2010), UAE was studied to be an efficient technique for flavonoid recovery (neohesperidin, tangeritin, hesperidin and diosmin) from citrus peel. However, the above work lacked in studying the antioxidant and antiproliferative activity of flavonoid extract extracted from citrus peels. Likewise, Khan et al. (2010) also found a remarkable enhancement in polyphenols particularly flavanones from orange peel using UAE treatment. Extract of flavanone percentage (70.3 mg of naringin and 205.2 mg of hesperidin/100 g FW), total phenolic content (275.8 mg of gallic acid equivalent/100 g FW), and extraction yield of 10.9% were obtained at a sonication power of 150 W, temperature 40 °C and solvent 4:1 (v/v) ethanol: water ratio. High performance liquid chromatography with diode array detector (HPLC-DAD) analysis performed on extracts obtained from purple sweet potato after ultrasound-assisted extraction had revealed that anthocyanin and non-anthocyanin compounds yield was significantly higher in UAE extract compared to conventional solvent extraction (Zhu et al. 2017). According to Li et al. (2021),

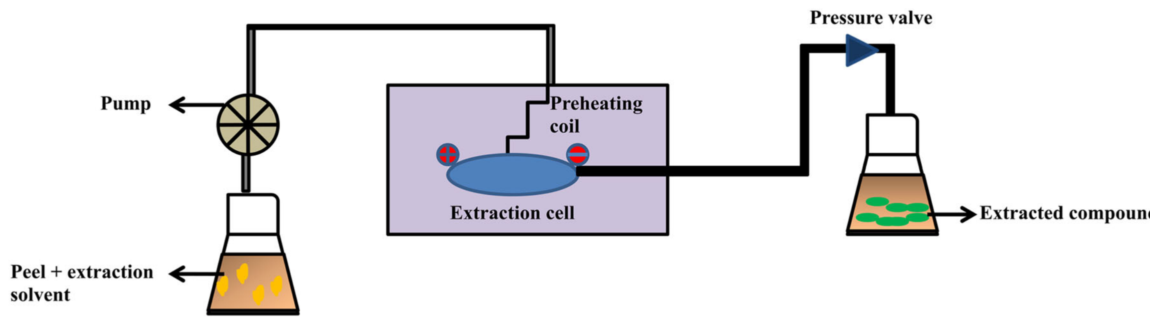

Figure 4. Schematic diagram of pressurized hot water extraction system.

the ultrasonic waves and their cavitation effect facilitates the acceleration of high extraction with improved yield of polyphenols and polysaccharides from green tea leaves at optimized values of 25 kHz, 40 W, 10 min. The thermogravimetric analysis (TGA) of obtained extract revealed better stability compared to extract obtained from conventional techniques. Henceforth, the findings of above study speculated that appropriate ultrasound assisted extraction is promising to aid the complexation of various food products during processing.

On the other hand Chuyen et al. (2018) assessed the potential of UAE and MWAE to particularly extract carotenoids from gac fruit peels. Authors reported that though UAE produced high extract yield compared to MWAE, the operational cost of UAE was much higher making it difficult for practical applications. Therefore, future work that develops an economical UAE system with reduced power consumption could be recommended. Khan et al. (2010) observed that UAE increased the extraction yield of pectin from orange peel by factor of 1.6 times ($R^2 = 0.948$) when compared to conventional technique. In spite of having many benefits, application of ultrasound technique for extraction procedure possess a major drawback. At enhanced level of pressure and temperature, the effect of ultrasound could result in development of H and OH radicals on matrix of peel. These free radicals trigger the free radical reactions through getting attached at exterior of cavitation bubbles formed during the process which could eventually result in targeted compound degradation. In general, through the above-reviewed works, application of UAE process in waste peel valorization can be proposed as a promising extracting technology for its efficient extraction of polyphenols, carotenoid molecule and flavonoid fractions. However, it is necessary to conduct further experiments to investigate the in vivo and in vitro biological characteristics of the F&V waste peel extract obtained through optimized conditions of UAE technique for its potent application in food industry.

4.3. Pressurized hot water extraction (PHWE)

Pressurized hot water extraction (PHWE) is another novel extraction technique applied for bioactive compound extraction from food and by-product matrices using hot water as the extracting solvent. The chief aspect of this process is the application of pressure and temperature values above 0.1 MPa and 100 °C (Duba et al. 2015) and below 374 °C and 22.1 MPa. These intense pressure and temperature bring about significant variations in properties such as surface tension and viscosity. The depletion in solvent surface tension promotes the solvent penetration into the pores of the peel matrix to significant level. These changes occurring during the process enhance the efficiency of PHWE as a novel extraction technique regards to reduction in extraction period and percentage of phenolic compound recovered. Numerous studies conducted initially to investigate the efficacy of PHWE for extraction of bioactive molecules from food and their by-product have been described PHWE to be function of following parameters: temperature, pressure, solubility of target molecule, flow rate, modifier characteristics and nature of additive used.

4.3.1. Mechanism of PHWE for extraction of targeted compounds from waste peel

The PHWE process is performed in an extractor chamber packed with desired weight of inert material most commonly sand (to avoid sample aggregation) and peel matrices. A schematic diagram of PHWE extraction system is shown in Figure 4. The extractive mechanism of PWHE contains few steps which are as described below: (a) desorption of targeted solute from active sites of peel matrix; (b) the peel matrix gets diffused with extraction solvent (hot water); (c) leaching out of solute to the solvent and trapping it in the collection vessel. The solvents are selected depending on the targeted solute (Lopresto et al. 2014). The chief cause for decreased usage of extraction solvent during PHWE extraction process is that this technique uses pressurized solvent of changing polarities under optimized condition of pressure (0.1 to 22.1 MPa) and temperature (100 to 373 °C). In reality, the application of temperature above 100 °C during PHWE results in formation of new antioxidant compounds owing to thermo-oxidation, caramelization and Millard reaction at these elevated temperatures. The initiation of these reactions transfer the electrons from bioactive compounds to form new complexes rich in antioxidant property. Furthermore, PHWE extraction process is capable to maintain pressure and temperature for every unique sample and demands extraction period shorter than an hour. This is the vital reason that makes PHWE to be an acceptable green technique for bioactive compound extraction from peel matrices.

4.3.2. PHWE applications for the novel extraction of bioactive compounds from waste peel

Few of the works evaluating the potential of PHWE to retain valuable molecule from F&V waste peels have focused on tannin recovery. In this line, Vergara-Salinas et al. (2013) analyzed and optimized PHWE process conditions (10.34 MPa for 5 min at 100 °C and 150 °C) to recover∼98–100% anthocyanin and tannin respectively from grape peel extract. In addition, logarithmic increase in degradation of extracted molecules at higher temperature was observed. Authors concluded that this was owing to the opening of pyrilium ring which leads to formation of colorless chalcone compounds. Likewise, Tunchaiyaphum, Eshtiaghi, and Yoswathana (2013) identified PHWE at 180 °C as an successful and environmentally friendly method to extract polyphenols and tannin from mango peels. On the other hand, Ko et al. (2011) proposed PWHE to be an excellent alternative to extract quercetin from onion peel waste (105 °C at 15 min). To contradict, it was observed that authors could not identify the optimal pressure value for quercetin extraction. The effect of PWHE process on the recovery of D-limonene from citrus peels (150 °C for 30 min with peel matrix: solvent ratio as 1:10) was studied by Lopresto et al. (2014). For first time, through this study authors described the significance of pre-drying and particle size reduction, yielding the result that oven drying of citrus peel and its fine grinding led to a two-fold yield increase in D-limonene. Nevertheless, further qualitative and quantitative study should be considered for future studies as it can provide information of practical leverage. According to the study conducted by Duba et al. (2015), it was reported that total polyphenol increased from 44.3 ± 0.4 to 77 ± 3 mg/g at PHWE temperature from 80 to 120 °C. Interestingly, this was the first research that reported kinetics (using two-site kinetic model) of PHWE extraction in bioactive compound recovery from waste peel. Henceforth, as future advances it can be recommended to use two-site kinetic model for predicting the yield recovery and as a primary tool for developing and designing PHWE process. Though PHWE is easier and simpler to operate as a pump and pressure gauge restrictor are not required the analyte residence period is mostly too long resulting in thermally sensitive compounds to degrade. Therefore, the time of PHWE have a great influence on process efficiency as well as on degree of degradation of targeted compound during process of extraction. Additionally, in extraction using pressurized hot water, equilibrium for dispersal of desired compound from the peel matrix to the chosen solvent will become stable after certain point of time, as the extractant volume is not variable. Henceforth, on this regard, the effectiveness of PHWE relies on ratio of scattering of desired analytes into the selected solvent. Overall, through this review it can be suggested that PHWE is an efficient process for extraction of polyphenols particularly tannins and volatile compounds henceforth commercialization of this technique will help the industrial scaling up of this process in F&V processing industries.

4.4. Pressurized liquid extraction (PLE)

Pressurized liquid extraction (PLE) is another novel extraction method that has found its wide application for extraction of phytochemical compounds from natural food matrices. PLE was first introduced as an extraction technique by Dionex Corporation for the extraction of anthocyanin from seaweed for pharmaceutical application (Mustafa and Turner 2011). Later, PLE technique has been reported to be successfully used for the anthocyanin, flavonoid and saccharide molecule extraction from various fruits and vegetables. This assures its wide potency to be used for extraction of phytochemical compounds from waste F&V peels. Furthermore, extraction using PLE was found to be more attractive process in food industry owing to its rapidity in process and decreased solvent consumption (Joana Gil-Chávez et al. 2013). Various works performed primarily to study the efficacy of PLE for extraction of phytochemical molecules from food matrix have outlined PLE to be function of subsequent factors: solvent polarity, toxicity of solvent, particle size, mass transfer rate, peel moisture content, temperature, pressure and extraction time.

4.4.1. Mechanism of PLE for extraction of targeted compounds from waste peel

In general, the treatment system of PLE consists of extraction cell, extraction vessel and a HPLC pump. A schematic diagram of PLE extraction system is shown in Figure 5. During the extraction process the peel sample is initially placed in an extraction cell till the chamber attains desired temperature and pressure values. Once the targeted values of variables are attained, solvent is pumped into the extraction vessel using HPLC pump (Carabias-Martínez et al. 2005). Now, the peel sample that has reached PLE temperature and pressure is moved to the extraction vessel and leaching of molecules commences here. After the extraction process is concluded, to remove the residual solvent at pressurized condition out of the extraction vessel noble gases such as xenon and argon is employed (Wang and Weller 2006). The mechanism of extraction for targeted compounds by PLE process is based on combination of two steps: (a) interaction of selected solvent and peel matrix and (b) use of high pressure and temperature. It can be elucidated that the high pressure used during pressurized liquid extraction process aids in production of hydroxyl group from polyphenols present in waste peels that leads to dissociation of reactive oxygen species and eventually aids in extract with antioxidant activity. In this method the temperature of the solvent is increased beyond the boiling point thus enhancing mass transfer, solubility and leaching rate of targeted molecule from peel matrix to selected solvent (Mustafa and Turner 2011).

4.4.2. PLE applications for the novel extraction of bioactive compounds from waste peel

Howard and Pandjaitan (2008) analyzed that the purity of flavonoid and polyphenolic compound recovered from

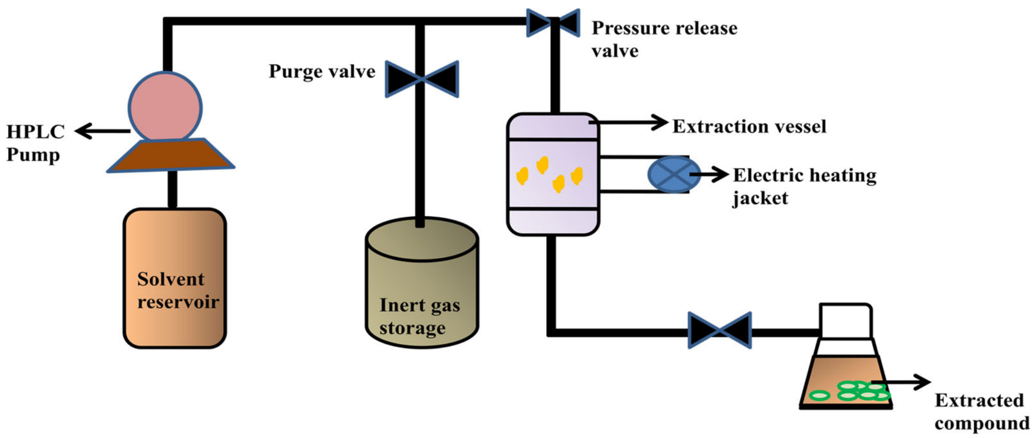

Figure 5. Schematic diagram of pressurized liquid extraction system.

spinach stem peels by PLE technique was about 91% and 93%. The antioxidant activity was also reported to be 2.1 times and 7.7 times higher in PLE when compared to conventional technique. Through another work, Cheigh, Chung, and Chung (2012) published a parallel statement with respect to the enhanced extraction yield of narirutin and hesperidin form citrus peels using PLE. Authors through above work described that citrus peel extract (narirutin and hesperidin) were studied to be effectual antioxidants when added to soybean and peanut oils, on the other hand were either ineffectual or performed as prooxidants when incorporated with vegetable oil-in-water systems. The above finding was accredited to interfacial occurrences, because of which hydrophilic citrus peels antioxidants continued attached to air-oil system, consequently providing improved safeguard against process of oxidation. However for above two studies it can be recommended that additional works are required to validate if the extracts possess antioxidant capacity when introduced within living organism (in vivo). Ju and Howard (2003) revealed that red grape peel extract obtained using acidified water by PLE at temperature 80–100 °C showed the highest yield of total anthocyanin (94% pure) compared to PLE with acidified methanol (90% pure).

Machado et al. (2015) investigated effect of PLE on extraction of total phenolics (TP) and anthocyanin (AA) from blackberry peel using acidified water as solvent. Authors identified temperature of 140 °C to be best PLE condition to yield maximum of TP (7.36 mg GAE/g) and AA (76.03 µmol TE/g) with purity of 91% and 90% respectively. Barrales et al. (2018), studied the potential of PLE on retention of phenolic compounds and reducing sugars from citrus peel and observed that PLE at 140 °C yielded reducing sugars and phenolic compounds two-fold and five-fold better compared to conventional techniques with significant purity. In spite of all this applications and advantage, PLE extraction technique is restricted to systematic uses mainly and possess large initial investment charge. In addition, at some instances the PLE can result in inactivation of extracted bioactive molecules because of the stress that gets developed through the mechanical impact of pressurized liquid extraction. In general, it can be summarized that high recoveries (∼above 90%) of mainly flavonoid, anthocyanin, reducing sugars molecules obtained using PLE; recommends this technique to be adaptable for quality control analysis with recommending its potential for industrial scale-up benefiting food, nutraceutical and pharmaceutical industries.

4.5. Supercritical fluid extraction (SFE)

In a wide aspect, SFE has confirmed itself as a notable green extraction method peculiarly in the case of solid matrices owing to its cost-effectiveness, ease in recovery of used solvent and reduced solvent consumption (Cruz et al. 2014). The most commonly applied fluid for SFE is CO_2 owing to its safe nature, low toxicity and low critical temperature (31.1 °C) (Akay, Alpak, and Yesil-Celiktas 2011). In addition, due to non-polar nature of CO_2 it is not suggested to employ it alone for polar natured polyphenol extraction, henceforth modifiers say ethanol, methanol and acetone are used. The modifiers enhance the solubility, solvating power and extractability of polyphenols (Majid et al. 2019). Interestingly, SFE has also been used for valorization of waste peel produced in F&V industry during its processing. The mechanism of extraction of bioactive compounds from waste peels can be elucidated as function of appropriate supercritical fluid selection, modifier property, peel particle size.

4.5.1. Mechanism of SFE for extraction of targeted compounds from waste peel

Carbon dioxide and water are the most widely used supercritical fluids owing to its GRAS status, economic feasibility and the synergistic characteristics of liquid and gaseous phases (Pereira and Meireles 2010). The SFE system consist of extraction vessel, pressure releasing valve, CO_2 pump, CO_2 condenser, CO_2 extract separator, temperature controllers, and heat exchanger (King 2014). During the process of extraction, initially peel material is fed into extraction vessel. The temperature controllers and pressure release valve attached to the extraction vessel maintains the preferred extraction parameters. In most instance, CO_2 is used and pumped at conditions ($Pc = 5.7$ MPa and $Tc < 5$ °C) to the main vessel. The CO_2 at inlet and exit of CO_2 pump is cooled using heat exchangers. Later, by application of

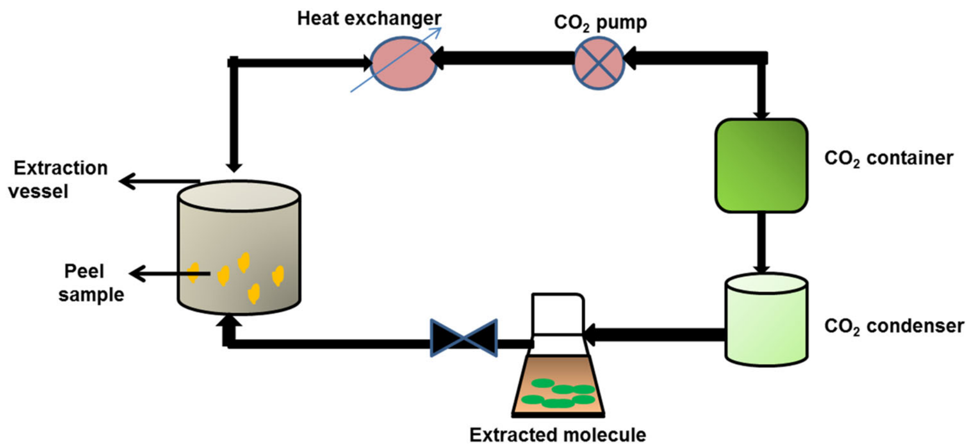

Figure 6. Schematic diagram of supercritical fluid extraction system.

combined pressure and temperature the salvation property of used SFE fluid is decreased and the desired phenolic extract dissolved in the fluid in extract separator is separated from using outlet valve positioned on the bottom side of the separator (Azmir et al. 2013). The course of SFE prolongs until highest revival rates of polyphenols are attained from the desired peel sample. The antioxidant properties of peel extract produced from SFE process can be chiefly accredited to the ability of this extraction method to avoid side reactions through free radicals neutralization. A schematic diagram of SFE extraction system is shown in Figure 6.

4.5.2. SFE applications for the novel extraction of bioactive compounds from waste peel

Roy et al. (2007) observed highest oil extraction yield from kabosu peel at SFE-CO_2 condition of 80 °C for 20 MPa. Investigators studied that oil yield after SC-CO_2 was 13 times greater than conventional hot-press method. Later, Chen and Huang (2016) discovered SC-CO_2 at (50 °C, CO_2 flow rate of 6 mL/min, 20 MPa) as an effectual method to extract out oleoresin from the peels of Tankan, Ponkan and Murcott (three citrus varieties). However, the activities of compound present in extract and their biological applications were left unstudied in both above works which demands future advances of this work. On the other hand, He et al. (2012) evaluated the effect of SC-CO_2 on flavonoid extraction from pomelo peel and revealed that optimized SC-CO_2 (80 °C, 39 MPa) condition showed greater flavonoid extraction. The phenolic compound from mango peel using SFE-CO_2 was found to be higher than obtained using conventional extraction technique (Tunchaiyaphum, Eshtiaghi, and Yoswathana 2013). Ndayishimiye, Getachew, and Chun (2017) used SFE-CO_2 (200 and 250 bars, 45 and 60 °C) for extraction of oils from citrus peels. To contradict, authors demonstrated that regards to oxidative stability of the extract an improved oil recovery was observed in conventional extraction using hexane compared to SFE-CO_2. Through another study, about eight phenolic compounds say (chlorogenic acid, *p*-hydroxyl benzoic acid, coumaric acid, caffeic acid, ferulic acid, protocatechuicacid, syringic acid and gallic acid) was extracted from potato peels using SFE-CO_2 technique (Singh and Saldaña 2011). Similarly, de Andrade Lima, Charalampopoulos, and Chatzifragkou (2018) aimed to investigate and optimize the extraction of carotenoid from carrot peels using SFE-CO_2 with ethanol as the modifier. For obtaining maximum carotenoid recovery (86.1%) with 97% purity the optimal conditions were 59 °C, 15.5% ethanol at 349 bar. In general, through some studies it was observed that the occurrence of humidity along with filths in laboratory-grade CO_2 may hinder the process of extraction. Therefore, a fluid based purifying setup might be a prerequisite to eliminate the contaminants which could enhance the instrument cost. Majority of SFE studies make use of non-polar solvent with great linkage to oxygen-based organic complexes. Nevertheless, the polar solvents say alcohols and acids display less solubility with bioactive compounds present in fruit and vegetable waste peels in absence of modifiers, thus making use of modifiers an inevitable factor. Investigators concluded that SFE-CO_2 is feasibly scalable, indicating that this technique can be effectively used for retaining high value-added molecule from F&V waste peel.

4.6. Pulsed electric field assisted extraction (PEFAE)

Pulsed electric field is the most widely recognized technology that has been demonstrated to enhance drying, diffusion and extraction process in food industry. Of the aforementioned PEF applications, preservation of food and extraction of valuable bioactive compound from food matrix, food residues and by-product have been most widely used applications in industrial level (Rajha et al. 2015). Recently, studies have demonstrated that among the emerging extraction technique, use of PEFAE stands to be the fundamental technique that is enduring a thoroughgoing technical assessment. Moreover, the efficiency of PEF assisted extraction technique for extraction of bioactive compounds depends on factors; pH, extraction time, specific energy input, treatment temperature, electric field strength, pulse shape, pulse width, pulse frequency, peel matrix density, size of peel sample, chemical properties of targeted compound to be extracted and other material properties.

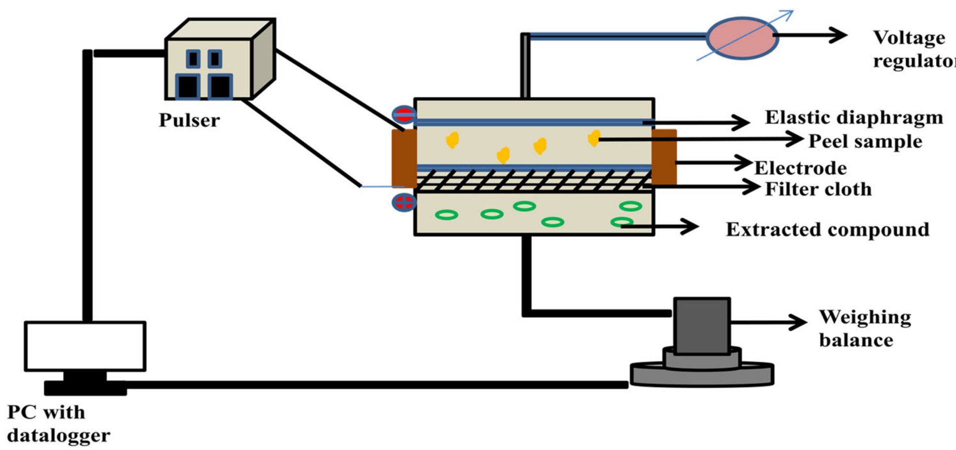

Figure 7. Schematic diagram of pulsed electric field extraction system.

4.6.1. Mechanism of PEF for extraction of targeted compounds from waste peel

In general, the PEF treatment unit comprises of treatment vessel, pulse generator, fluid handling- monitoring system and two electrodes (between which sample is placed). A schematic diagram of PEFAE system is shown in Figure 7. As the electric field is applied for a small fraction of microseconds into the peel sample the fundamental cell structure changes and rupturing of cell membrane initiates (Misra et al. 2017; Vorobiev et al. 2004). This phenomenon is known as electroporation and is the chief principle that elucidates the PEF process. The main mechanism of pulsed electric field for extraction process is as described below: Electric fields produced using PEF application splits the molecules in cellular membranes of the waste peel on the basis of their charges owing to their dipole nature. When the threshold value of peel matrix membrane potential attains one volt, repulsive forces get developed among the charged component, which in turn initiate pore formation and increases the peel matrix permeability. Usually, to apply PEFAE technique a simple circuit with exponential decay is employed (Bryant and Wolfe 1987). Depending on the design of extraction vessel the PEF technique of extraction can be used in a batch or a continuous mode. Nevertheless, it has been reported that an optimum electric field (500 and 1000 V/cm) retards temperature elevation, which has significant effect on waste peel cellular matrix. PEF assisted extraction has been revealed as an established tool to particularly recover targeted molecules (polyphenols, oils) from various bio resources respect to its economic and feasible point, chiefly owing to its potency to soften and rupture cell membranes, thus smoothening the leaching of intracellular bioactive compounds (Guderjan et al. 2005; Puértolas et al. 2010; Rocha et al. 2018). The antioxidant activity of peel extract obtained through PEFAE could be owing to the reason that electric field and the electroporation developed within the matrix aids in chelation of metal ions present within bioactive complex in peel matrix which retards the oxidation process. Interestingly, PEF assisted extraction process has also been used for the recovery of valuable bioactive compound from F&V peel waste, the few recent works are described below.

4.6.2. PEFAE applications for the novel extraction of bioactive compounds from waste peel

The efficiency of PEFAE to improve extraction of antioxidants from mango peel was focused by Parniakov et al. (2016). Authors reported that PEF treatment (13.3 kW/cm, 60 °C, 1000 kJ/kg) led to significant increase in polyphenol (mangiferin, quercetin, ellagic acid) yield extraction. Furthermore, it was also identified that mango peel extract possessed high antioxidant activity on vegetables oils oxidation when investigated at temperatures above 65 °C, owing to the existence of ellagic acid molecule. The impact of PEFAE technique for recovery of polyphenol compound from citrus fruit waste peel (pomelo, orange and lemon) was investigated by El Kantar et al. (2018). The results reported that PEF treatment at 3 kV/cm and 10 kV/cm increased the recovery of polyphenols from peels up to 22 mg/g DM for orange and 16 mg/g DM for citrus. To contradict, a minor reduction in the polyphenols yield from pomelo peel was observed after PEF treatment and authors described that this could be owing to the higher density of pomelo peels. Another experiment was conducted with the goal to valorize peel of red prickly pear by extraction of its red color (betanin pigment) using PEFAE (Koubaa et al. 2016). Authors revealed that this high recovery in pigment yield (at 20 kV/cm, for 50 min at 20 °C) was owing to diffusion of betanin molecule from intracellular to extracellular media due to the cell permeabilization induced by PEF technique. Peleg model was used to explain the extraction kinetics of total betanin from pear peel as it showed a R^2 value close to one. However, comparing above all three works it was revealed that studies relating microstructural analysis were not considered though structure is an important property to be maintained to preserve cell integrity and can be recommended as future studies.

Parniakov et al. (2014) identified that application of PEFAE at 4 kV/cm and 400 pulses in papaya peels yielded total polyphenols (85%) compared to raw peel sample (75%). Likewise, Hossain et al. (2015), also studied that when electric field magnitude increased during PEFAE, leaching of polyphenolic molecule enhanced to significant rate within potato peels. The results obtained through above works demonstrate the feasibility of PEF assisted extraction

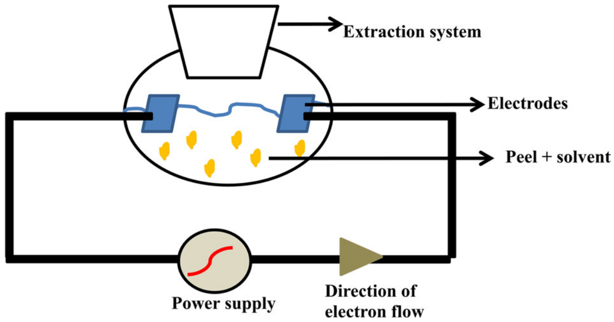

Figure 8. Schematic diagram of pulsed ohmic heating assisted extraction system.

technique to recover polyphenols mainly rich in antioxidant compounds, particularly flavonoids, natural pigments, total phenolic compounds, and protein from waste peels. However the findings produced through few studies revealed that use of PEF for extraction of bioactive compounds was found to be more proficient in retention of water-soluble compounds. The electric field generated throughout the process could slightly enhance the body temperature of the operator if operated for long period. However, the promising outcomes of PEF have proven to be an assuring technique to recover nutritionally important molecules eliminating the application of extraction solvents, decreasing the temperature and employing neutral pH environment thus promoting installation of PEF set up at industrial level in order to scale up the extraction process cost-effectively.

4.7. Pulsed ohmic heating assisted extraction (POHE)

In most instances, use of modest electric field at environmental temperature may not be sufficient to extract out the targeted bioactive molecule particularly, polyphenol compounds that are strongly bonded with peel cellular membrane to its full potential. Henceforth, use of POHE, that aids in rising temperature owing to the ionic movement as result of ohmic heating process with electric field maintained at moderate range ($E < 100\,V/cm$) have proven to be a robust extraction tool to recover higher yield of phenolic compounds (Jaeschke et al. 2019). Contrarily, pulsed ohmic heating is practically applied extensively at alternating current (AC) power source. Henceforth this extractive method is widely acceptable to food industries owing to the ready accessibility of AC current and the decreased chance of electrolysis. In addition, POHE application have been reported to be efficient in inactivating enzymes present in foods, maintaining organoleptic properties, product forming, product reformation, microbial inactivation and clarification (Gavahian et al. 2016; Jittanit et al. 2017; Kim et al. 2017). Surprisingly, the influence of pulsed ohmic heating for extraction of bioactive compounds from food product, residues and by-product has also been studied. The efficacy of POHE for extraction of bioactive compounds from waste peel matrices depends on critical factors say: temperature, frequency, field strength, process time, electrical conductivity, peel matrix specification.

4.7.1. Mechanism of POHE for extraction of targeted compounds from waste peel

Using POHE, a comparatively faster extraction rate is achieved owing to the combination of the following two mechanisms: (1) permeability enhancement due to the applied electric field, (2) volumetric heating. Sensoy and Sastry (2004) discovered that use of POHE results in electromechanical compression of peel cellular matrix and leads to expanded cell structure (owing to intact arrangement of peel cells) resulting in increased permeability of peel membrane leading to pore development and to high extraction of targeted compounds. The mechanism of electro-permeabilization initiates the molecular leakage owing to enhanced trans-membrane potential (Knirsch et al. 2010). Secondly, traditional extraction systems use conventional heating equipment which relies on both mode of heat transfer that is conduction and convection. On the other hand, POHE follow a vivid mechanism that is heat gets generated within the material simultaneously as electrical energy gets converted to heat energy. Henceforth, this method of volumetric heating in POHE increases the temperature much faster than traditional and other non-conventional extraction technique and enhancement in applied voltage increases the heating rate of the process (Pare et al. 2014). This abrupt increase of temperature damages the cells, disrupt the structure and leach out targeted molecule to the surrounding chamber. The trans-membrane potential developed during POHE process enhances degree of hydroxylation. As the antioxidant activity relies on position as well as the number of hydroxyl groups present in a compound, the generation of hydroxyl compound to peel extract aids in its antioxidant activity. Henceforth, due to mechanism of volumetric heating and trans-membrane potential the pulsed ohmic heating assisted extraction technique have been reported to speed up the extraction process of various food matrices and their by-product including waste peels. A schematic diagram of POHE extraction system is shown in Figure 8.

4.7.2. POHE applications for the novel extraction of bioactive compounds from waste peel

In a recent study, Coelho et al. (2019) identified that POHE treatment (4,6,11 V/cm) of tomato peel resulted in enhancing the rutin and polyphenol recovery by 77% and 58% more compared to control sample. Interestingly, for first time researchers also observed an increase in bioavailability of lycopene at temperature from 70–88 °C, below and above which degradation was observed owing to oxidation. Coelho et al. (2017) observed appreciable boost in antioxidant activity and phenolics content from tomato peels when extracted with POHE at 40 °C and 70 °C ($p < 0.05$). However, from above two studies performed it can be inferred that future studies are required to assess the role of electrical frequency and field on extraction mechanism. On the other hand, Pereira et al. (2016) applied POHE for phytochemical extraction from potato peels and revealed POHE to be a promising technique for recovery of anthocyanin's and phenolic compounds from vegetable peel at decreased power consumption. El Darra et al. (2013) obtained about 36%

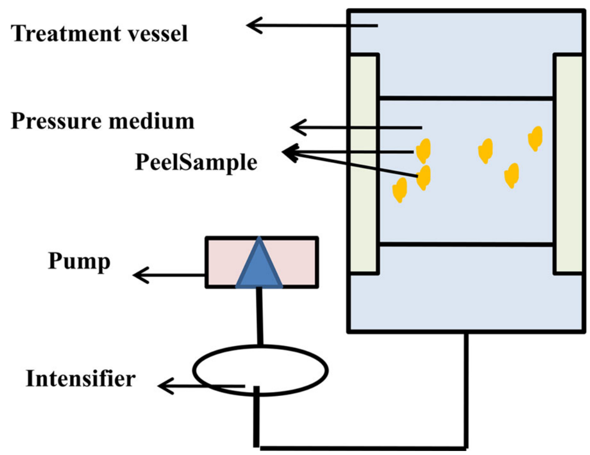

Figure 9. Schematic diagram of high hydrostatic pressure assisted extraction system.

higher polyphenolic extract yield from grape peel sample when subjected to POHE condition of 400 V/cm at 50 °C. Henceforth through this research it can be concluded that POHE is an assuring technique for future use in the valorization of waste peels from F&Vs processing industries eliminating use of hydro alcoholic solvent. Moreover through certain works it was identified that pulsed ohmic heating assisted extraction demands the need of a predictive, and determinable models of heating configurations. It has also been reported that at times POHE could result in development of hot-spots within the sample matrix demanding the need of installing a real-time temperature checking system for discovering hot spots and cold-spots during the extraction process. POHE also demands the need to develop a satisfactory quality and safety guarantee procedures for the commercialization of POHE technology. However, this extraction process proves to be a promising technique to be applied as a substitute to traditional organic solvent methods to extract both carotenoid and polyphenolic compounds cost-effectively.

4.8. High hydrostatic pressure assisted extraction (HHPE)

High hydrostatic pressure/High pressure processing is a green technique involves the processing that is performed at a very high pressure range of 300–100 MPa at ambient temperature for about 3–5 min (Oey et al. 2008). The major application of HHP in food processing involves, microbial decontamination, surface modification, enhancement of nutritional properties and product transformation. Later, HHPE was identified to be an active alternative extraction technique for plant materials (food product and their by-products) and was studied to be a rapid and more effective process than other extraction methods. The mechanism of extraction of bioactive compounds from waste peels can be elucidated as function; peel particle size, presence of interfering molecule, chemical nature, extraction conditions, sample moisture and equilibrium constant). Recently, HHP assisted extraction technique was acknowledged by the United State Food and Drug Administration as it solely requires only power for its operation without generating any waste making it a hundred percent environmentally friendly technology.

4.8.1. Mechanism of HHPE for extraction of targeted compounds from waste peel

In recent times, numerous researchers (Altuner et al. 2006; Barba et al. 2015; Corrales et al. 2009) delineated that HHP assisted extraction do not produce any negative effect on structure and characteristics of bioactive compounds and provides an increased extraction yield at a shorter processing time. The application of pressure of range 300–1000 MPa enhanced the rate of mass transfer thus boosting the diffusion of secondary metabolites, permeability of cell leading to in-phase progression. The selectivity of peel cellular membrane decreases after HHPE due to charged proton deprotonation, protein denaturation, interference of salt bridges and hydrophobic-hydrophilic bond disruption (Xie et al. 2018). During HHPE, the compounds were found to be readily available for extraction till equilibrium point. That is, greater the hydrostatic pressure more solvent flowed into the cell resulting in higher compound permeation in cell membrane resulting in increased extraction yield. Furthermore, Shouqin, Jun, and Changzheng (2005) identified that during HHP assisted extraction as samples are suddenly subjected to high pressures it results in formation of high pressure difference between exterior and interior of peel cell membrane leading to quick permeation yielding high quantity of extract. A schematic diagram of HHPE extraction system is shown in Figure 9.

4.8.2. HHPE applications for the novel extraction of bioactive compounds from waste peel

Strati, Gogou, and Oreopoulou (2015) demonstrated that HHPE carried out at 700 MPa for 10 min resulted in six-fold increase in carotenoid yield from tomato peel compared to solvent extraction process. Authors observed that this increase in yield was owing to denaturation of carotenoid binding protein induced by HHP. Likewise, Xi (2006) reported an enhancement in extracting lycopene from tomato peel after processing at 500 MPa for 12 min at 20 °C, which they accredited to the certainty that HHPE causes fissures in tissue and results in release of lycopene. Recently, Xie et al. (2018) studied the performance of HPPE (200 MPa for 5 min) on pectin extraction from potato waste peel. Moreover, they also reported that HPPE extracted pectin showed improved emulsifying properties when used in further food applications. Likewise, Naghshineh, Olsen, and Georgiou (2013) investigated the extraction of pectin from lime peel using HHPE and observed a linear relation between extract yield and applied pressure. However, at 400 MPa a decrease in extraction yield was observed. Authors explained that this could be owing to the irreversible breakage of intramolecular and intermolecular enzyme owing to high pressure treatment resulting in decline of activity. Casazza et al. (2012) evaluated the potential use of HHPE to recover phenolic molecules from grape peels. The authors inferred that high yield of polyphenols (60.7 mg GAE) with efficient radical scavenging activity was obtained using HHPE technique. An interesting remark of this study was that appreciable enhancement in antioxidant activity was observed in encapsulated grape peel extract compared to non-encapsulated extract molecule, thus disclosing the potency of nano-emulsions in biological delivery systems. However despite of all these advantages of HHPE, the major and the prevailing limitation HHPE technology in the industrial level is connected to great inceptive investment and absence of information concerning process control variables.

4.9. Enzyme-assisted extraction (EAE)

Enzyme assisted extraction technique has gained research importance particularly owing to various benefits. Generally, enzymes are compounds that are significantly specific and efficient (Lotfi et al. 2015). EAE may be considered as a substitute technique appropriate to gentle environmental situations, devoid of huge quantity of untargeted compounds usually and has lesser affect on the surroundings. The below section describes the use of EAE of phytochemical constituents from waste peels. The major advantage of use of EAE method for extraction of bioactive compound from waste peel involves: (a) EAE technique is an elevated bioactive molecule yielding methodology as in this process cell walls are ruptured and preferred bioactive compounds are generated out. (b) EAE liberates out the redundant cellular wall components, and thus enhances the system transparency (c) It gives the advantages of elevated catalytic competence and conserve unique value of the peel samples to a significant degree (Shen et al. 2008).

4.9.1. Mechanism of EAE for extraction of targeted compounds from waste peel

The rupture of cellular components is the decisive process of extraction for various bioactive molecules accessible within the cell membrane. EAE is regards to the capability of enzymes to break down the cellular ingredients and interrupt the integrity of peel cellular components, under gentle process circumstances, henceforth permitting the proficient extraction and discharge of the targeted bioactive compounds from waste peels (Choi et al. 2015). As substrates and enzymes combine together, the enzyme molecule configuration varies to a most favorable fit for the interface among enzymes and substrates. The alteration in the product geometry varies the strain and stress on the substrate resulting in cleavage of bonds and thus aiding the reaction to proceed. As the concentration of substrate increases, the incorporation of the enzyme could augment the kinetics of reaction, until the concentration of substrates gets limited (Gardossi et al. 2010). There rises a linear proportionality among the concentration and rate of substrate till the concentration of enzymes becomes restraining. Enzyme assisted extraction of waste peels depends on the operational parameters say: extraction time, reaction temperature, concentration of enzyme, pH system, and substrate particle size. Through study by Zhu et al. (2018), it was observed that polyphenols extracted from knot of rhizome applying enzyme-assisted extraction coupled with filtration confirmed promising results. The use of pectinase/cellulase produced a significant impact on extraction yield, with the maximum yield being 4% attained at cellulase/pectinase ratio of 2:1. The nine important polyphenols recovered in this study after treatment from rhizome knot permeate and extract included: B-type procyanidin dimer·H_2O, chlorogenic acid, (+)-Catechin, (-)-Epicatechin, propyl gallate·H_2O, caffeic acid, rutin, B-type procyanidin dimer, and (-)-Epicatechin-3-gallate. Henceforth, the above work demonstrated the promising prospective of the enzyme-assisted extraction for rhizome knot valorization. The most generally applied enzymes for bioactive compound extraction from waste peels include protease, cellulase, α-amylase, hemicellulase, pectin methyl esterase, and β-glucosidase (Sowbhagya and Chitra 2010).

4.9.2. EAE applications for the novel extraction of bioactive compounds from waste peel

Khodaei et al. (2016) demonstrated that potato peel wall is predominantly rich in rhamnogalacturonan-I pectin source. The impact of extraction properties of pectinase enzyme catalyzed extraction of potato peel RG-I and its relations were also studied in above work applying response surface methodology (RSM). The enzyme concentration and cell wall composition were the main important factor affecting yield of pectin, galactose and arabinose percentage. Under finest conditions, that is 181 units of pectinase, 90% pure RG-I with galactose content of 72% was recovered from potato peels. In another study Enzymatic, acid and water extraction of pectin from peels of kiwifruit was compared by assessing the percentage of neutral sugar, molar mass, pectin yield, degree of branching and viscosity (Muñoz-Almagro et al. 2017). Pectin from kiwifruit peels was extracted using Celluclast. Extraction condition at 25 °C and pH of 3.70 for 30 min, yielded the maximum yield (~4.5% w/w) when collated to the yield obtained through acid and water based extraction techniques (~3.6–3.8% w/w). The impact of pooled enzymatic/physical conditions on the physic-chemical attributes of pectin obtained from Yuza peel was compared against chemically-yielded pectin (Lim et al. 2012). Pectin containing reduced methoxyl percentage and low viscosity that enclosed about 55% galacturonic acid was retained with a yield of about 7.3% with no other chemical components, whose extraction yield was equivalent with extraction using chemical techniques (8.0%). On the other hand, the RG-I area was not prominent (17.1%) as the β-glucanase applied chief focus on the hydrolysis of cellulose. Conventional acid based extraction and EAE of apple peels were also studied (Wikiera, Mika, and Grabacka 2015). Like before study, Celluclast 1.5 L, was applied to apple peel in concentration of 25 to 70 μL per gram. The treatment was carried at pH 4.5, 50 °C for a period of 18 h. The authors observed that the least concentration of Celluclast enzyme produced a recovery percentage of pectin as 15.3%. The recovered pectin was studied to be rich source of fucose and arabinose respectively. Wikiera et al. (2015) used three

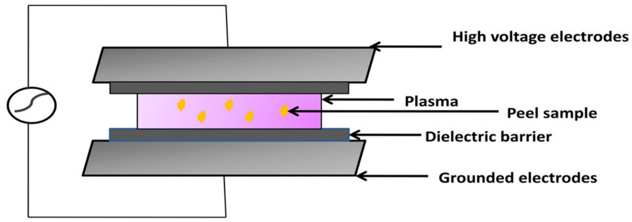

Figure 10. Schematic diagram of dielectric barrier discharge plasma assisted extraction system.

diverse industrially obtainable enzymatic preparations (Celluclast, Econase and Viscoferm) were to extract out molecule from pectin from apple peels. Celluclast extraction produced a yield of 19%, followed by Viscoferm (18%) and Econase of about 12% extraction yield. Furthermore, it was reported that pectin obtained from Celluclast enzyme was superior in neutral sugar recovery. EAE offers diverse advantages counting yielding of elevated extract purity; removal of insensitive extraction parameters with decreased equipment deterioration; and elimination of sugars and color pigment from extracted peel samples are minimized. However, there are few limitations, presently; obtainable enzymes might not entirely break down peel cellular components, henceforth restricting enhanced pectin extraction. Furthermore, the small substrate concentration creates upgradation of the extraction technique cumbersome (Khodaei et al. 2016).

4.10. Dielectric barrier discharge plasma extraction (DBDE)

The non-thermal plasma or cold plasma is produced by the use of an electric field into a gas. This energy aids the liberated electrons to hasten and ionizes the molecules of gases that generate extra free electrons which in turn aggravate new ionizations. Furthermore, an energized electron generates dissociations of molecules, with the development of newly formed radicals and atoms (Takamatsu et al. 2015). Excited molecules, when recurring to the steadier phase, give out surplus vigor in the form of electromagnetic radiation, comprising UV radiation. Accordingly, the plasma is comprised principally by atoms in an energized state, including free radicals, radicals, nitrogen species, ozone, electrons, positive ions, negative ions and so forth. The precedent few years have noticed enhanced interests in the use of cold plasma extraction technique in food sector (Hou et al. 2008). Dielectric barrier discharge (DBD) plasma, a type of non-thermal plasma, had been majorly applied for inactivation of enzymes or inactivation of microorganisms all through the processing of food and many other applications including extraction of phytochemical constituents from food and their byproducts.

4.10.1. Mechanism of DBD for extraction of targeted compounds from waste peel

DBD is capable to cease down particular bonds for the extraction of bioactive compounds from waste peels by the demolition of the secondary configuration using released free radicals or by comprehending chemical variations of side chains throughout the deed of numerous chemically vigorous species comprising the plasma (Misra et al. 2016). DBD might also be applied to extract out bio macromolecules present in waste peels comprising protein, chitin, polysaccharides and chitosan (Hou et al. 2008). On the other hand, replacement of methoxyl chain at third and fifth position using –OH group under plasma exposure as reported in case of syringic acid increases the antioxidant activity. Through few works conducted in prior by Andreasen et al. (2001) it can be identified that hydroxycinnamic acids displays greater antioxidant activity related to equivalent hydroxybenzoic acids. This was owing to the fact that on exposure to plasma the acid groups present in hydroxycinnamic acid gets replaced with OH group which scavenges the free radical present and thus enhances the extract antioxidant activity. High-energy electron generated by DBD, permeates into water molecule, releasing hydroxyl free ions, that attacks on the pectin linkage and ruptures the bioactive components into minor chain molecule and aids in its extraction. A schematic diagram of DBDE extraction system is shown in Figure 10.

4.10.2. DBD applications for the novel extraction of bioactive compounds from waste peel

S. (2018) optimized the condition for extraction of pectin from pokan peel using DBD technique and applying RSM. A significant pectin yield of 27% was proficiently achieved under the subsequent setting of pH 2, voltage of 40 V, at S/L 1:30 for 5.5 min. Furthermore, enhanced extraction period (>5.5 min) or high voltage greater than 40 V lowered pectin recovery, as degradation of pectin occurred owing to prolonged revelation to plasma system. Furthermore, the precise mechanism of this extraction technique yet awaits advance investigation. The use of DBD plasma for extraction of bioactive compounds from waste peels has not attained enough consideration, henceforth, there is only one study limited to this extraction technique till date. The major remarkable feature of extraction technique by DBD plasma is its enhanced selectivity on targeted molecules (Umair et al. 2019). However it was observed that extraction using DBD plasma requires reduced energy consumption and could be employed with no extra chemical compounds. As a result, it is regarded as a very capable technique for the revival of bioactive compounds from plant materials and their byproducts. On the other hand, few limitations constraining practical use of DBD plasma assisted extraction warrants to be discussed say the reduced life span of plasma system, enhanced operational cost, and the alteration of physicochemical attributes of the targeted compounds during extraction process.

4.11. Extraction using green solvents

Green solvents are nonvolatile, decomposable, nonpoisonous, biodegradable, and do not encompass a great energy for its production. Green solvents are basically classified into three groups, viz., bio-based, deep eutectic solvents (DES), and supra molecular solvents. Substituting an unsafe solvent using a safer substitute at extraction process is important and, in certain instance, new tasks and restrictions can ascend owing to the various physicochemical factors of the chosen solvents (Breil et al. 2016). Through this section, the extraction prospective of green solvents for waste peel is discussed. DES (mixture of Brønsted and Lewis acids and bases) have shown great potential for extraction of bioactive from fruit and vegetable waste peel. Through works it has been observed that the extraction yield and time for bioactive molecule differed according to the kind of DES, the arrangement of targeted molecule, the temperature during extraction and the application extra energy DES was reported to be efficient for the extraction of anthocyanin molecule from grape peels and polyphenols from citrus peels (Manousaki et al. 2016). It was observed that as extraction period ranged from 11 min to one day and temperature enhanced from 40–90 °C the yields of targeted compounds increased significantly. Bio-based solvents ethyl lactate and ethyl acetate respectively had been applied to yield out phenols and carotenoids from tomato peels (El-Malah et al. 2015) and polyphenols and ellagic acid from pomegranate peel (Masci et al. 2016). At temperatures generally of 30–80 °C and subsequent extractions to attain satisfactory retrieval of bioactive molecules that is greatly reliant on time of extraction and use of supplementary drive say ultrasound or microwave. Supramolecular (SUPRASs) solvents are nanostructured solvents formed in colloidal state through rapid, consecutive occurrences of co-acervation (Caballo, Sicilia, and Rubio 2017). Co-acervation is elucidated as “the parting into two fluid states in colloidal systems. The part which is greatly turbid in colloid phase is the coacervate, and the further part is the equilibrium solution.” A very limited works have been reported for the bioactive extraction from waste peels for extraction of betaine from beet leaves (Mohammadzadeh et al. 2018) and anthraquinones from aloe peel (Tan, Li, and Xing 2012). However, the assessment of the commercial feasibility and application at industrial level for bioactive extraction from waste peel stands to be the major limitation to widen the use of green solvents. Additionally, works explaining the assessment of diverse kinds of green solvents for the same application or of a green solvent with conventional techniques could be appropriate to further comprehend the benefits and drawbacks of the use of green solvent technology.

5. Major combination extraction technologies for bioactive compound extraction from waste peels

Along with budding drift for environmentally approachable techniques, food industry is primarily concerned in decreasing manufacturing price via either enhancing process speed or augmenting yield of extract. Though till date there exist no extraction process alone as a model extraction process, there are techniques to accomplish an equilibrium among production costs, quality of product and solvents employed. Expeditious advancement has happened in improvement and progress of extractive techniques. As reported by Giacometti et al. (2018), efficient extraction applies attempting to enhance the purity of extract, extraction yield and shorten processing time. This earmarked target would be achieved either through one robust technique or with several hurdles, performed at the same time period in a synergistic or in an independent manner. For a broad time, the research community has concerted on the development of a extraction technique with higher efficiency of targeted molecule recovery will not only valorize waste peel, but also will be beneficial in lowering the operational cost. Furthermore, when two extractive technologies are applied on to peel sample, the effect is not solely A + B, but every element will be driven by the other. From, above reviewed works it can be envisaged that conventional and novel green extracting techniques have been proven to be promising technique at industrial scale for bioactive compound extraction from waste peel individually, but the additional approach of merging two-or more extractive technique: conventional-conventional; conventional-nonconventional; nonconventional-nonconventional have been proven to achieve higher efficiency at the industrial level. Through the works summarized in before sections, innovative extraction methods say enzyme-assisted, microwave and ultrasound extraction had been applied as robust tools to deliver better productions and advanced products regards to waste peel. Associations of ultrasound, microwave and enzyme assisted technique was found to be of best choice to attain the desired balance better.

5.1. Ultrasound-assisted enzymatic extraction (UAEE)

In present times, few works have studied the pooling of enzyme-assisted and ultrasound-assisted extraction techniques, generally termed as ultrasound assisted enzymatic extraction (UAEE) for leaching out of phytochemicals (Mehmood et al. 2019). UAEE is regarded as a grouping of two interrelated extraction techniques to facilitate further benefits. In enzyme assisted extraction, enzymes endorse retrieval of targeted bioactive molecules rupturing and destroying the cell membranes. Nevertheless, enzymes are not capable of hydrolyzing the cellular matrix similar to cell walls (Wu et al. 2014). In addition, ultrasound assisted extraction had been reported to have complementary influence compared to EAE, since the bubbling effect generated through USAE might substantially dislocate and rupture the medium to facilitate enzymatic reaction and subsequent discharge of intended molecules. Similarly, enzymes could not enhance solvent mass transfer, targeted molecules and enzymes themselves contained by or even exterior to the matrix. Therefore, various physical processes say shaking are frequently applied in enzyme assisted extraction to augment mass transmission, amid which ultrasound assisted process is a perfect choice since it could augment mass transfer not just from exterior but likewise inside the medium of matrix (Chemat, Rombaut, Sicaire, et al. 2017). Additionally, it was studied that as the power of ultrasound increases the contact area among matrix phase enhances, and this could bare

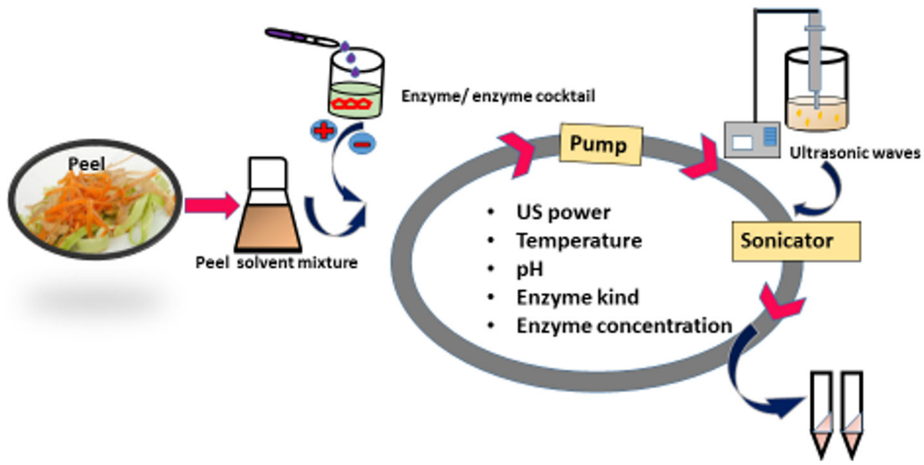

Figure 11. Schematic diagram of ultrasound-assisted enzymatic extraction system.

further substrates in enzyme assisted system toward the enzymes and aid in discharge of higher yield of desired bioactive compounds. A schematic diagram of UAEE extraction system is shown in Figure 11.

UAEE was reported to hasten phytochemical extraction from various parts of plant tissue through several researchers. UAEE had been applied to extract bioactive molecules from plant sources say leaves, fruits, peels and wheat bran (Chen et al. 2012; Chen et al. 2014; Wang et al. 2014; Zhang et al. 2015), wherein UAEE displayed the capacity for extract yield enhancement. Qian et al. (2018) studied on retrieval of a water soluble polysaccharide named DFPWSP-1 from dragon fruit peel using UAEE. The findings displayed that greater recovery of DFPWSP-1 was achieved when ultrasound and enzyme were given concurrently on samples or in order, compared to enzyme assisted extraction or ultrasound alone. The ideal extraction parameters for highest yield of DFPWSP-1 were cellulase capacity of 104 U, US power of 105 W, treatment time of 2.06 h, and solvent to sample volume of 8.5 mL g^{-1}. The concurrent UAEE technique provided a hurdle effect with highest DFPWSP-1 yield of 20.28%. Likewise, Tang et al. (2016) applied UAE and EAE in order to yield out soluble dietary fiber from pomelo peel. Authors identified that use of US enhanced the enzyme process efficiency, and UAEE created enhanced extraction yield for dietary fiber (4.67%) when compared to enzyme assisted and ultrasound assisted alone. UAEE had also been used to leach out lycopene in tomato peels from tomato processing industries (Tang et al. 2016). Through their observation, a multi-process method of extraction comprising ultrasound trailed by enzyme assisted method followed by extraction from tomato peels using micro emulsion ensued an boosted extraction of lycopene whereas with UAEE technique, as compared to traditional extraction techniques, ultrasound assisted and enzyme alone. Through another study, US bath and viscozyme was used for polyphenol retention from peels of pomegranate fruits (Nag and Sit 2018). The optimum values attained were US time of 41.45 min, viscozyme concentration of 1.32 mL/100 mL, incubation temperature of 44.85 °C and time 1.82 h to extract out polyphenols and flavonoids to values 19.77 mg GAE/g and 17.97 mg QE/g. Junjian et al. (2013) explained the influence of UAEE method to extract polyphenols from apple. Authors observed an increased enhancement in end yields of polyphenolic compounds from apple peel at extraction parameters: temperature 37 °C, time 37 min, and cellulase enzyme concentration 2500 U g^{-1} compared to enzyme assisted, ultrasound assisted and any traditional techniques.

5.2. Microwave-assisted enzymatic extraction (MWAEE)

Presently, enzyme assisted and microwave assisted had been identified as assuring technology for phytochemical compound extraction owing to advantage of enhanced extraction efficacy, effortless handling, reduced energy use, and low solvent consumption. MWAEE comprises the association of microwave treatment and enzymolysis that could rupture cell wall, and enhance cell wall permeability. Therefore, the desired molecules inside the targeted cell could be shifted more effortlessly into solvent (Cheng et al. 2015). The right portion of Figure 12 illustrates schematic representation of MWAEE, which demonstrates that enzymatic process could be performed pre or post to microwave treatment. In regards to incorporation of enzyme subsequent to microwave treatment, the chosen samples requires a cooling procedure to preserve in particular temperature so as to elude immobilization of successively used enzyme, otherwise even unswervingly on to enzyme ideal working. Few applications regards to MWAEE from fruit and vegetable peel source are presented and discussed in the subsequent portions.

MWAEE, the grouping of microwave and enzyme (cellulase: 3000 U/g), was used for extraction of soluble dietary fiber from grapefruit peel (Gan et al. 2020). The MWAEE not just enhanced the structural properties of dietary fiber, but also enhanced functional characteristics, particularly by showing improved binding ability to oil, cholesterol, water, and nitrite ion. Henceforth, MWAEE possesses a significant prospective for the use of grape peel extracted dietary fiber in functional food industry. Li et al. (2013) explained the use of green MAEE technique devoid of any organic compounds and attained a greater oil yield from seed coat of yellow horn seed. The optimization findings revealed that oil yield reached a value of 55.8% using MWAEE in temperature of 60 °C at 30 min. Associating to conventional extraction techniques, they observed a comparable yield in extraction temperature of 90 °C in 90 min in the optimized values. Zhang et al. (2013) had developed MAEE technique for polyphenol extraction from peel of peanut beans. It was observed that extraction yield of polyphenols attained values equal to 1.75% at optimal values of 2.6 min irradiation time, 0.81% of cellulase at pH 5.5 in 66 °C for 2 h. With the optimized values, an evaluation was performed between MAEE with extraction techniques say EAE and UAE. It was observed that the polyphenol yield with MAEE (1.75%) was greater compared to 1.62% and 1.56% obtained through EAE and UAE, proving the greater proficiency of MAEE compared to other techniques. The cause for enhanced efficiency of MAEE unit could be owing to pooled enzyme activity owing to radiation produced from microwave that ruptures the cell membranes enhancing the surface area among liquid and solid state phase, as well as interaction of solvent upon intended molecule. Another study on practicability of MWAEE for yielding out polysaccharides from peel of Schisandrachinensis fruit (Cheng et al. 2015). The optimal values for extraction were identified as MW irradiation of 10 min at temperature 48 °C in pH 4.20 for period of 3 h, using the enzyme papain, cellulase, pectinase at 1.5% each. In addition authors also associated MWAEE with UAE and EAE. The outcome displayed that MWAEE technique resulted in enhanced yield of targeted polysaccharides at reduced temperature and small processing period compared to EAE and UAE. Another study was conducted in which, microwave-assisted enzymatic extraction (MWAEE) technique was used for concurrent extraction of geraniin and corilagin with deionized water (Yang et al. 2010). The optimal values of extraction were as mentioned below: MW power of 500 W, pH of 5.2, solvent to solid ratio of 40 mL/g, MW temperature 33 °C, treatment time of 9 min and cellulase concentration of 3600 U/g. In above optimal condition, the yield of geraniin and corilagin attained was 19.82 and 6.79 mg/g that augmented by 72.95%, and 64.01% respectively, when compared to control ones.

5.3. Microwave-ultrasonic assisted extraction (MWUAE)

MWUAE, the association of ultrasonic and microwave assisted, is the best considered and likely technique as a hurdle extraction method. In practice of MWUAE, samples could be made quick and extraction technique is increased that make MWUAE an economical extraction technique using aids of better efficacy, reduced extraction period, and improved yield (Cravotto et al. 2008). US could increase the solvent movement into sample medium, encourages the solubility of solvable molecules, and enhances the area of contact by rupturing cell membrane and improving mass transfer. In the meantime, MW enhances temperature of sample speedily, augmenting solubility rate, mass transfer, and increasing desorption of targeted molecules from matrix, ensuing in improvement of yield (Milman and Zhurkovich 2017). The association of MW and US energy could be fairly flexible in MWUAE. The microwave and ultrasound might be used consecutively or as sequence as demonstrated in Figure 12.

In recurrent way, the MW or US wave's breaks for a particular time period all through the extraction process, the power on/off modules used irradiations could be harmonized or self-regulating. The harmonized process is generally used when enhanced energy flow into the treatment unit, particularly when zero refluxing unit is connected in extraction unit wherever increased solvent vaporization can take place, in specific respect to solvents say methanol, ethanol etc. that has low boiling point.

The intermittent process might aid to decrease the evaporation rate or regulate solvent temperature (Marić et al. 2018). The MW or US energy in order might be accomplished with two separate apparatuses (ultrasound and microwave equipments), and treatment with one equipment trails another irradiation in other equipment. The concurrent irradiations could establish increased energy and subsequent heat to extraction medium in particular time, whereas it requires specifically fabricated arrangement to integrate simultaneous irradiations in one container. A MWUAE unit was designed with a probe to initiate ultrasound waves into the chamber that is in microwave oven. The fabrication of MWUAE apparatus needs to have safety device setup, for instance, an explosion might occur in case a probe located within microwave cavity or owing to US probe that is built of materials say Pyrex, polyether ether ketone, quartz and so forth. The inherent construction of probe prepared by above resources can permanently destroy and extreme safely operational power of above materials was studied only to be 90 W. In addition, it has also been studied that power higher value owing to the probe material never hindered the use of MWUAE since the concurrent radiation using MWUAE unit demands reduced power compared to ultrasound or microwave irradiation. Upon seeing to employ probe fabricated from metallic substances, Marić et al. (2018) predicted the proposal for consecutive MW and US irradiation, in which samples move over a reactor in MW cavity followed to next reactor within US space. This proposed design permits the use of commercially accessible US probes, implying an advanced working bound of MW and US power permissible. Table 4 specifies many current studies using MWUAE.

Numerous works have used sequential MWUAE method that might possibly decrease or could even avoid the deprivation of intended bioactive extract MWUAE technique from fruit and vegetable waste peel (Bagherian et al. 2011; Liew et al. 2016; Vázquez et al. 2014). Investigators described that the association of two methods produced improved yields and was found to be effectual in extraction of heat subtle molecules. Bagherian et al. (2011) explained the impact of US as a pretreatment process subsequent to MW extraction for extraction of pectin from peel of grapes. The dried peel powder solution was subjected to US treatment first underneath intermittent US irradiation for 1800 sec, and later on adding HCl, it was subjected to MW power of 450 W for 600 sec. The findings explained the pectin yield through MWUAE technique (31.88%) was greater when compared to conventional technique (19.26%), microwave assisted

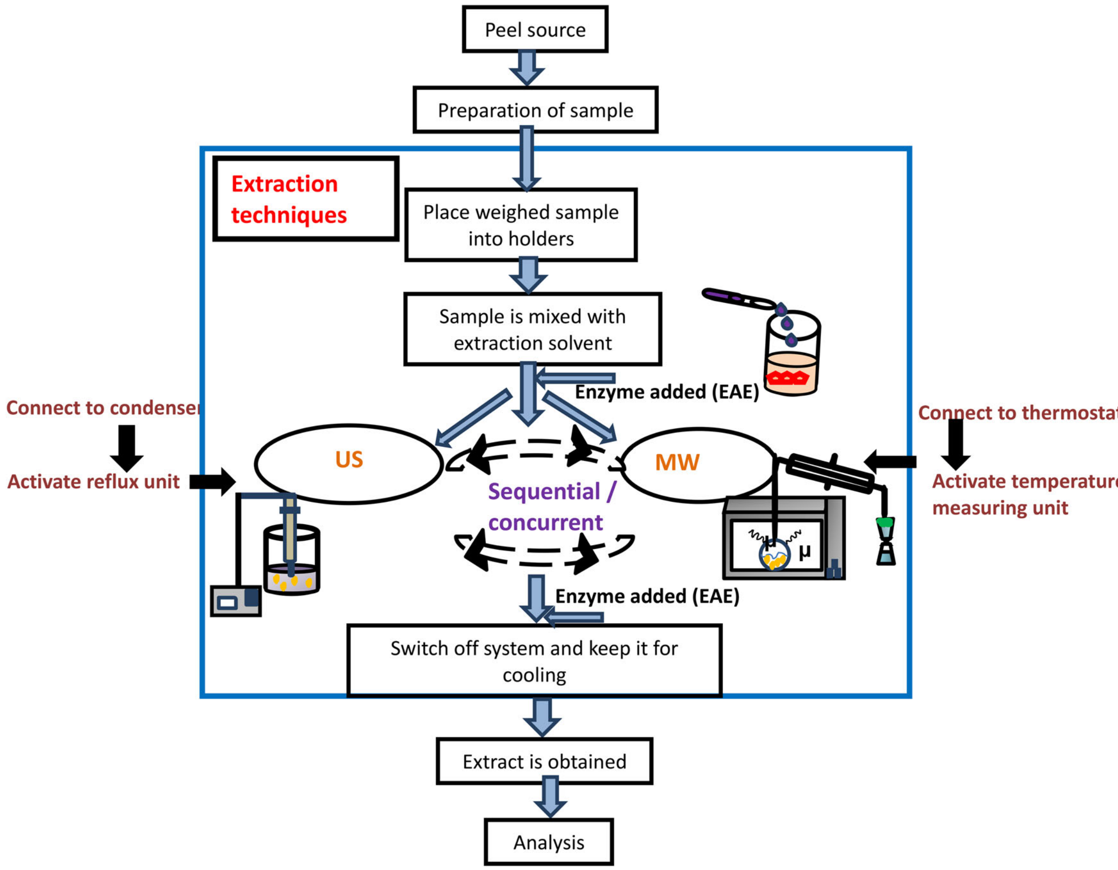

Figure 12. Schematic diagram of synergistic effect of UAE, MWAE, and EAE.

(27.81%), and ultrasound assisted UAE (17.92%). Furthermore, The MWUAE extract presented the finest impact on qualitative properties of obtained pectin compared to extract produced out of ultrasound, microwave and traditional. Liew et al. (2016) identified the optimal values for sequential MWUAE process on peel of pomelo fruit with citric acid and performed a comparative study between MWUAE, UAE and MAE. In optimized conditions, MWUAE produced the maximum yield subsequent to MAE, and lastly UAE. Another work was performed that determined extraction of lycopene from tomato peels by means of MWUAE compared to UAE (Lianfu and Zelong 2008). The authors identified that lycopene was extracted out in values of 97.4% and 89.4% in MWUAE and UAE treatment processes, correspondingly. MWUAE displayed greater efficacy, owing to cavitation of US waves and warming influence of microwave radiation.

6. The application of other combination extractive technique for bioactive compound extraction from waste peels

Corrales et al. (2008) measured the effect of emerging technologies such as HHPE (600 MPa), PEF (3 kV/cm) and UAE (35 kHz) for anthocyanin extraction from grape peels. The authors identified that total phenolic composition of treated sample was about 50% greater than untreated sample. Furthermore, enhanced antioxidant activity of grape peel extracts by PEF four-fold, HPP three-fold and ultrasonic two-fold was observed when compared to control. Casazza et al. (2012) efficiently applied two subsequent process for the extraction of phytochemical compounds from mango peels both at temperature of 40 °C at 30 MPa. Primarily, supercritical CO_2 was used, proceeded by use of ethanol under pressure. Kehili et al. (2017) extracted out carotene and lycopene as oleoresin from a tomato waste peels applying solvent extraction process using ethyl acetate, hexane ethanol and by process of supercritical CO_2 extraction. Solvent extraction technique using ethyl acetate, hexane, and ethanol produced 320.35, 608.94, and 284.53 mg/kg of lycopene extract from dry tomato peels, respectively.

Safdar, Kausar, and Nadeem (2017) compared the effect of ultrasound assisted extraction (UAE) and maceration technique to extract the polyphenols and flavonoids from mango peel. It was observed that solvent concentration level of 80% was more effectual than 50% or 100% concentration during both maceration and UAE. Liew et al. (2016) optimized sequential ultrasound-microwave assisted extraction of pomelo peel for pectin extraction as 6.40 min irradiation at 643 W and pH 1.8 to yield 56.88% of pectin. Authors also observed that pectin galacturonic acid isolated using combined extractive process was higher than obtained by individual ultrasound and microwave extraction process. More recently, same authors (Liew et al. 2019) extracted pectin from pomelo peel produced during the industrial processing of pomelo by conventional extractive technique UAE and PHWE. Regards to extract yield, quality of extract and energy efficiency UAE was found to be promising for

Table 3. Results published on the application of hurdle technologies for extraction of bioactive compounds from fruit and vegetable waste peel.

Hurdle technique	Peel matrix	Extracted compound	Treatment condition	Salient results	Reference
Solvent extraction process + Supercritical CO_2	Tomato peels	Carotene and lycopene	Solvent extraction technique using ethyl acetate, hexane, and ethanol Supercritical CO_2 extraction at 4 g CO_2/min for 105 min at 400 bar for 80 °C	Solvent extraction technique using hexane, produced 608.94 mg/kg of lycopene and supercritical CO_2 extraction produced lycopene extract of 728.98 mg/kg	(Kehili et al. 2017)
UAE and maceration	Mango peel	Polyphenols and flavanoids	Ethanol and methanol at concentration 50, 80 and 100% and S/L ratio 1:20 was used & UAE 50, 60 kHz	Concentration level of 80% was more effectual during both maceration and US-AE. Regards to purity US-AE extract was more pure	(Safdar, Kausar, and Nadeem 2017)
UAE + MWAE	Pomelo peel	Pectin	UAE: 20–40 kHz for 12–28 min MWAE: 350–650 W at 1.7–2.3 min	Optimized sequential UAE of for pectin extraction as 6.40 min; irradiation at 643 W at pH 1.8 for pectin yield of 56.88%. UMAE > MUAE > MWAE > UAE	(Liew et al. 2016)
UAE + PHWE	Pomelo peel	pectin	UAE: Sonication time (12–28 min); pH (1.7–2.3) PHWE: Pressure (30–65 bar); Time (90–120 min)	Maximum yield of pectin was obtained at UAE for 27.5 min at pH: 1.8 and PWHE of 30 bar for 120 min. Efficiency: PWHE > UAE	(Liew et al. 2019)
UAE + MWAE	Phenolic compounds	Jackfruit peels	160 W for 20 min using ethanol (63%) with S/L: 34 ml/g.	Purity of phenolic in extract enhanced from 13.59 to 49.07% with robust antioxidant activities	(Jiang et al. 2019)

MWAE: microwave assisted extraction; UAE: ultrasound assisted extraction; PHWE: Pressurized hot water extraction; PLE: pressurized liquid extraction; PEF: pulsed electric field assisted extraction; HHPE: high hydrostatic pressure assisted extraction

extraction of high molecular pectin and PWHE for low molecular pectin. Moreover, a productive extraction process respect to ultrasound combined with microwave assisted extraction was applied to extract phenolic rich compounds from jackfruit peels (Jiang et al. 2019). Authors identified that purity of phenolic in extract enhanced from 13.59 to 49.07% thus possessing it to be a promising source of robust antioxidant activities for food industry. Therefore, through this study it is proposed that jackfruit peel could be helpful in expansion of large-scale batch adsorption-desorption unit for antioxidant phenolic production from peels.

In general, non-conventional extractive techniques have been well studied for extraction of bioactive from waste peel. However, their combinations with conventional processes or other non-conventional process are generally less explored. Therefore, more work is required to be carried out to expand their applications in F&V waste processing. The important works summarizing the effect of hurdle extractive techniques on the recovery of high value-added bioactive compounds from F&V waste peels are summarized in Table 3.

7. Comparison of efficacy for conventional and non-conventional extraction techniques

In this review, we analyzed the studies involving application of conventional and non-conventional technologies pertinent to extraction of bioactive from F&V waste peel. Soxhlet, maceration, decoction, infusion and percolation were discovered to be the conventional techniques that proved their efficacy for extraction of targeted group of molecules from F&V waste peel. Of the five major technologies, Soxhlet was found to be effectual for polyphenolic compound extraction from F&V peel. Maceration was found to effectively enhance the extraction of polyphenolics and flavonoid molecules, besides other heat-liable bioactive. However, the technique of Soxhlet and maceration extraction arises with disadvantage such as high consumption of liquid organic solvents, solvent toxicity, incremented energy consumption and chemical waste. Meanwhile, studies conducted on mango peel revealed that decoction extractive technique was highly suitable for heat stable molecules (Safdar et al. 2017). Though decoction method was reported to be cheaper compared to Soxhlet and maceration techniques, the inability to dissociate complex matrices has limited its application. While infusion and percolation aid in extraction of bioactive compounds (mineral and tannin) from waste peel, their low extraction yield has limited their application. Henceforth, for bioactive compound extraction using conventional techniques from waste peel regards to purity and yield maceration can be suggested more promising as it is less costly and suitable method for small scale industries compared to novel green extraction methods. However, the finding was greatly limited to estimation of phenolic, flavonoid content and total yield as comparison.

In recent years, much attention has been paid to PEFAE, POHE and HHPE as potentially viable extraction technologies. This is owing to their potential to recover a wide range of targeted molecules (polyphenols, flavonoids, protein, rutin, anthocyanin, tannin and lycopene) from waste peel in

Table 4. Salient results inferred on the application of conventional and non-conventional technologies to improve the extraction processes of bioactive compounds from fruit and vegetable waste peels.

Extraction technique	Temperature & pressure	Volume of solvent	Extraction period	Type of waste peels applicable	Applications and/or beneficial effects	References
Soxhlet	Under heat and at atmospheric pressure	Modest	Extremely long	Peels of citrus and berry fruits	Antioxidant activity, Food coloring	(Caldas et al. 2018; López-Bascón and De Castro 2020)
Maceration	Ambient temperature and atmospheric pressure	High	Extremely long	Peels of bean vegetable	Antifungal, Anti-inflammatory and antioxidant molecule	(Ćujić et al. 2016)
Decoction	Under heat and at atmospheric pressure	–	Moderate	Peels of tropical and exotic fruits	Antimicrobial activity	(Omeroglu et al. 2019; Petkova et al. 2020)
Infusion	Under heat and at atmospheric pressure	Modest	Moderate	Peels of citrus fruits	Antioxidant activity, Dietary supplement	(Hidayat and Wulandari 2021; Wendimu and Tekalign 2020)
Percolation	Periodically under heat and atmospheric pressure	High	Extremely long	Peels of tropical fruits	DPPH activity and antibacterial property	(Hidayat and Wulandari 2021; Ravanfar et al. 2018)
MWAE	Ambient temperature and atmospheric pressure	Modest	Shortened	Peels of tropical and berry fruits	Antioxidant, antimicrobial and free radical scavenging activity	(Bagade and Patil 2021)
UAE	Ambient temperature and atmospheric pressure	Modest	Shortened	Peels of berry vegetables, citrus fruits	Antimicrobial, antioxidant and anti-proliferative activity	(Ravanfar et al. 2018)
PHWE	Under heat and high pressure	Modest	Shortened	Peels of allium vegetables, berry fruits, tropical fruits and citrus fruits	–	(Plaza and Turner 2017)
PLE	Under heat and high pressure	Modest	Shortened	Peels of leafy vegetable, citrus fruits and berry fruits	Antiproliferative and antioxidant molecule, Food coloring	(Figueroa et al. 2018; García et al. 2021)
SFE	Under room temperature and high pressure	Very reduced	Shortened	Peels of citrus fruits and root vegetable	Antioxidant, antimicrobial	(Uwineza and Waśkiewicz 2020)
PEF	Ambient temperature and atmospheric pressure	No solvent used	Shortened	Peels of stone fruit, citrus fruit, tropical fruit and root vegetable	Antioxidant activity	(El Kantar et al. 2018; Yan, He, and Xi 2017)
POHE	Moderate temperature and atmospheric pressure	Modest	Shortened	Peels of berry fruits, root vegetable	Antioxidant activity	(Kim et al. 2017)
HHPE	Room temperature and increased pressure	No solvent used	Shortened	Peels of berry vegetable, root vegetable and citrus fruits	Antioxidant activity	(Scepankova et al. 2018)
EAE	Modest temperature and atmospheric pressure	No solvent used	Shortened	Peels of tropical and stone fruits	Antioxidant activity, antioxidant molecule	(Gligor et al. 2019; Marathe et al. 2017)
DBDE	Room temperature, atmospheric or high pressure	No solvent used	Shortened	Peels of citrus fruits	Antioxidant activity Food coloring	(Farias, Rodrigues, and Fernandes 2020; Fernandes, Santos, and Rodrigues 2019)

continuous operation up to 5000–10,000 kg/h, with sometimes good selectivity. MWAE, UAE, DBDE, SFE-CO_2 can be concluded as an efficient novel technology respect to high recovery level of phenolic compounds (especially phenolic pigments). However, MWAE and UAE were generally found to be less selective compared to PEF and HHPE, restricting their industrial applications in some cases.

8. Status of scaling up non-conventional extraction techniques to industrial level

To validate the suitability of selected waste peel and extraction technology, the ensuing step could be to scale up the aforementioned green technologies to industrial level. During previous ten years SFE, UAE, MWAE, had been

Table 5. Effect of conventional and non-conventional extraction technologies on physical, chemical, nutritional properties and bioactive compound quality of fruit and vegetable waste peels.

Extraction technique	Processing effects on bioactive compounds in waste peels during extraction	Chemical, physical and nutritional parameters affected during extraction in waste peels	Reference
Soxhlet	Peel pigment, flavonoids	Enhances lipid oxidation	(Caldas et al. 2018)
Maceration	↑Flavonoids, ↑Anthocyanin, ↑Polyphenols	↓Color ↓Sugar content	(Safdar et al. 2017)
Decoction	↑Syringic acid	↑pH ↓Volatile oil	(Omeroglu et al. 2019; Petkova et al. 2020)
Infusion	↑Polyphenols and ↑minerals	↑Pore size ↓Color ↓Pungency	(Xu et al. 2008)
Percolation	↑Tannin ⬌Polyphenols	↓Sugar content	(Hidayat and Wulandari 2021; Ravanfar et al. 2018)
MWAE	↑Polyphenols and pectin	⬌Extract color ⬌ Purity	(Mirzadeh, Arianejad, and Khedmat 2020; Vinatoru, Mason, and Calinescu 2017)
UAE	↑Polyphenols, carotenoids and flavonoids	⬌Sugar ⬌Mineral concentration	(Grassino et al. 2020; Safdar et al. 2017; Vinatoru, Mason, and Calinescu 2017)
PHWE	↑Flavoring agent, polyphenol and tannin	⬌Vitamin E ↑Saponin ↓Color	(Chen and Huang 2016; Ndayishimiye, Getachew, and Chun 2017)
PLE	↑Flavonol and polyphenolic pigment	↑Acidity ↑Color	(Barrales et al. 2018)
SFE	↓Oils	↑Surface area ↓Flavor & acidity ↑Saturated fatty acid	(Chen and Huang 2016)
PEF	↑Phytosterols	Inhibit the oxidation of low-density proteins	(El Kantar et al. 2018)
POHE	↑Bioflavonoid's and carotenoid	⬌ Particle size, ⬌nutrition ⬌Color ⬌flavor	(Coelho et al. 2019)
HHPE	↑Pectin, phenolic compound and carotenoid	↑Color ↑Minerals ↑Storage stability	(Grassino et al. 2020; Pereira et al. 2016)
EAE	↑Pectin ↑Galacturonic acid	↓Viscosity ⬌Neutral sugar ↑Pectin yield	(Muñoz-Almagro et al. 2017)
DBDE	↑Pectin	⬌Quercetin ⬌Color	(Farias, Rodrigues, and Fernandes 2020; Fernandes, Santos, and Rodrigues 2019)

Where (↓) refers to decrease in the level when compared to other extraction technique; (↑) refers to increase in the level when compared to other extraction technique; (⬌) refers to neither increase nor decrease in the level when compared to other extraction technique.

established in majority of the countries across the world, whereas enzyme assisted extraction, high hydrostatic pressurized extraction and dielectric barrier discharge extraction have demonstrated narrow possibilities for commercialization (Chemat and Khan 2011). Nevertheless, the other green extraction techniques summarized in this review had not been industrialized for extraction of bioactive compounds yet. Henceforth, the application of these novel green extraction techniques to extract bioactive from waste peel still stresses further efforts to achieve industrial application for through molecule extraction (Roselló-Soto et al. 2016). The total techniques summarized in this review appear commendable for extraction of bioactive molecules. Consequently, it is important to evaluate and introduce the definite grouping of green extraction technique and sample (waste peel), looking into consideration the characteristics of targeted molecule. The prevailing limitation of the above techniques in the commercial scale is associated to great initial installation coast and absence of information concerning process regulating attributes. To eliminate these difficulties, it is significant to optimize the process dependent parameters. Respect to the sample, progression of competent non-conventional extraction technique proficient of safeguarding bioactive compound property and its stability are the significant contemplation respect to industry. Use of a cooling unit or a competently innovative method is important to drop temperature respect to method scaling up to industrial level. The present statistical data's revealed by commerce in zone of food, chemical and pharmaceutical industries specifies that extraction of targeted bioactive may be improved at a decreased operative cost by application of these green extraction techniques. Therefore, a systematic valuation of charges related with originating, functioning and upholding the process and product line aiding to the practical use of these evolving techniques to food, chemical and pharmaceutical industries still warrants the need of future research.

9. Future perspectives

Numerous studies have reported on extraction of bioactive from fruit and vegetable waste peels. The significant amounts of peel waste obtained from fruit and vegetable processing often lead to not only environmental pollution, but also the loss of bioactive contained. Table 4 provides a summary of important remarks identified from this review of conventional and non-conventional technologies. Any suitable extraction method could be adopted in industry, provided process optimization is achieved with respect to yield, quality, and economics. Owing to the legal and environmental issues (as mentioned earlier), interests in the use of water as solvent and development of nondestructive techniques for bioactive compound extraction is growing (Chemat et al. 2019; Jerome, Singh, and Dwivedi 2019). Various emerging extraction methods, for instance MWAE, UAE, PEF, have been extensively considered for extraction of phenolic compounds, flavonoids, minerals and heat liable compounds from fruit and vegetable waste peel at laboratory scale. Majority of these technologies are expected to find strong niche utility in the food industry, eliminating conventional processes (based on heating and large solvent to solute ratio), either solely or via additive interaction.

Lately, significant focus has been positioned on decrease of carbon imprint owing to the progression of smart cities globally. Chemical and food industries can contribute a vital part in attaining this aim through accepting methodology that is environmentally suitable with the aid of non-conventional extraction techniques. Non-conventional sustainable extraction techniques discussed above in this review have been proven to be prominent methods for the extraction of bioactive components from waste peel (Miękus et al. 2019). The novel paradigm transference in application of bioactive components in various industries say food, chemical, pharmacy, and textile proposes on big hand the recognition of requirement for good lifestyles and parallelly, the requisite for chemical trades to apply harmless and apposite method for extraction within biomass (Azmir et al. 2013). Development of a extraction processes and pretreatments exclusively for bioactive molecule recovery from waste peel could not only valorize the peel waste but also aid in diminishing price of functional and nutraceutical foods. Table 5 illustrates the effect of conventional and non-conventional extraction technologies on physical, chemical, nutritional properties and bioactive compound quality of fruit and vegetable waste peels. Further, the end results could include elimination of artificial chemicals in food formulations. Advancements in extraction methods with complete elimination of organic solvents will be also of great implication toward an enduring bioprocess.

10. Conclusions

Through this review, a gamut of modern extraction techniques were identified that could potentially be scaled-up for recovery of bioactive molecules from fruit and vegetable waste peel. It could be envisaged that, the primary objective of above all discussed extraction techniques was to yield final bioactive extracts of high purity. Though most of the influential factors of each reviewed extraction technique possessed the capability to augment extraction, in some instance the lack of appropriate judgment resulted in purity degradation of final extract. However, out of the five conventional techniques summarized the most suitable techniques regards to extract purity can be categorized as: maceration > decoction > Soxhlet > infusion ≥ percolation. Meanwhile, non-conventional extraction technologies have proven to be more efficient in yielding extract with high purity, thermal stability and maximum quantity recovery when compared to conventional techniques. Henceforth the general order of most suitable non-conventional extraction techniques regards to purity of bioactive compounds from F&V peels through this review can be stated as: PLE > POHE > PEF > HHPE > MWAE > UAE > DBDE > SFE > EAE > PWHE. Various researchers have suggested that the introduction of bioactives recovered from waste peels as dietary supplements lessen the risk of developing cardiovascular issues and physiological disorders. In addition, in many cases the peel extracts are also linked with antimicrobial, antifungal and antiproliferative effects. Thus, waste peel extracts could potentially be marketed as natural antimicrobials for inhibiting microbial growth in food products. The substitution of unsustainable inorganic/organic solvents in extraction methods with aqueous based green solvents and use of non-conventional, non-thermal approaches is an area of strong focus among researchers. Applications of hurdle effects of non-conventional approaches have also been observed to be highly promising respect to extract purity, economic feasibility and environmental safety. Parallelly, to assure thermal stability of extracts, bioactive encapsulation is increasingly being practiced. It is anticipated that technologies assuring to be most environment friendly would be most favored by industry. That said, a comprehensive cost analysis of these extraction methods remains to be performed, for assessing the leverage and profitability over the relatively low cost of initial raw material. Utilization of green extraction approaches for waste peel utilization will facilitate additional compensation to the fruit and vegetable processors, besides reinforcing sustainability. The end beneficiaries of the extracts are expected to be food, cosmetic, chemical and pharmaceuticals sectors.

Disclosure statement

There is no conflict of interest among authors

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