



# Ultrasound assisted extraction (UAE) of bioactive compounds from fruit and vegetable processing by-products: A review

Kshitiz Kumar<sup>a</sup>, Shivmurti Srivastav<sup>a</sup>, Vijay Singh Sharanagat<sup>b,\*</sup>

<sup>a</sup> Department of Food Processing Technology, A. D. Patel Institute of Technology, New Vidynagar, Gujarat, India

<sup>b</sup> Department of Food Engineering, National Institute of Food Technology Entrepreneurship and Management, Haryana, India

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## ABSTRACT

Growing fruit and vegetable processing industries generates a huge amount of by-products in the form of seed, skin, pomace, and rind containing a substantial quantity of bioactive compounds such as polysaccharides, polyphenols, carotenoids, and dietary fiber. These processing wastes are considered to be of negligible value compared to the processed fruit or vegetable due to lack of sustainable extraction technique. Conventional extraction has certain limitations in terms of time, energy, and solvent requirements. Ultrasound assisted extraction (UAE) can extract bioactive components in very less time, at low temperature, with lesser energy and solvent requirement. UAE as a non-thermal extraction technique is better equipped to retain the functionality of the bioactive compounds. However, the variables associated with UAE such as frequency, power, duty cycle, temperature, time, solvent type, liquid-solid ratio needs to be understood and optimized for each by-product. This article provides a review of mechanism, concept, factor affecting extraction of bioactive compounds with particular focus on fruit and vegetable by-products.

## 1. Introduction

The consumption of fruit and vegetable has increased with growing consumer awareness for nutritious and balanced diet. The production and processing of fruit and vegetables has increased manifold and so has the losses in the form of waste and by-products. Food and Agriculture Organization (FAO) has estimated the fruit and vegetable losses and waste upto 60% of the total horticulture production. The by-product generated during processing of fruit and vegetable industry alone account for the 25–30% of the horticulture product loss [72]. Fruit such as oranges, pineapple, apple, grapefruit, chokeberry and vegetables such as potatoes, carrot, onions and asparagus are processed to produce value added products. The by-product of such fruit and vegetable processing comprises of seed, skin, pomace, rind which are not commonly consumed but possess valuable bioactive compounds particularly phytochemicals and secondary metabolites entrapped in tissue [40,71]. In many cases the concentration of bioactive compounds have been reported more in these by-product than the edible part of the fruit [7,30]. For example the concentration of phenolic compound is 15% higher in peels of lemons, grapes, oranges and seeds of avocado, jackfruit, and mangoes than pulpy part of fruit [34,77]. Similarly potato peel has been reported to contain 50% of the total phenolics in potato [92]. The health benefit of these compounds includes anti-allergenic,

anti-inflammatory, anti-microbial, anti-oxidant, antithrombotic, cardio protective, and vasodilatory effects. The valuable bioactive compounds, which should be utilized for development of functional or enriched food, are lost in want of economically viable extraction techniques. In recent years, the outlook towards the fruit and vegetable by-product has changed. One reason for this change is the demand of natural bioactive compounds such as pectin and antioxidants having potential nutritional and therapeutic value together with their presumed safety and profitability.

The recovery of bioactive compounds involves extraction as a key step, which is achieved through methods such as solvent extraction, mechanical expelling, supercritical extraction, and microwave extraction. The recoveries of compounds through these methods have limitations such as use of extra solvent in solvent extraction, low yield in mechanical expelling, large capital in supercritical fluid extraction, and requirement of aqueous phase in microwave assisted extraction [75]. Compared to these methods, UAE has advantages such as less time and energy requirement, extraction at low temperature and retention of the quality of the extract. UAE extract bioactive compounds from fruit and vegetable waste and by-products using high intensity sound waves. The ultrasound waves cause disruption in the plant tissue through physical forces developed during acoustic cavitation and helps in release of extractable components in the solvent in very less time by enhancing the

\* Corresponding author.

E-mail address: [vijaysinghs42@gmail.com](mailto:vijaysinghs42@gmail.com) (V.S. Sharanagat).

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mass transport [4].

Ultrasonics are successfully employed for the extraction of polyphenols, carotenoids, aromas, polysaccharides from plant matrices (whole plant and by-products both). The variables associated with UAE such as frequency, power, duty cycle, temperature, time, solvent type, liquid solid ratio needs precise control for optimum extraction. The individual as well as interactive effects of these variables have been studied by several researchers on the extraction of bioactive compounds from the fruit and vegetables by-products. There are good reviews available regarding UAE from food and natural product [81,14], extraction of specific component such as pectin using novel techniques [1], antioxidant compounds from plant food [69]. A complete review focussed on all aspects of UAE of bioactive compounds from fruits and vegetable by-products is currently not available. Hence, the objective of the present review is to provide compressive information on mechanism, contributing factors and bioactive compounds extracted using UAE from the fruits and vegetables by-products. We have also summarized the gaps and future research area in extraction of bioactive compound from fruit and vegetable waste using UAE.

## 2. Concept and mechanism of UAE

Ultrasound-assisted extraction (UAE) uses ultrasound energy and solvents to extract target compounds from various plant matrices [29]. Ultrasound are the mechanical waves having frequency ( $> 20$  kHz) higher than audible frequency range of human hearing (20 Hz to 20 kHz). These waves consist of a series of compression and rarefaction cycles that can be propagated through solid, liquid or gas medium inducing displacement and dislodgement of the molecules from their original positions. At high intensity sound wave, the negative pressure during rarefaction exceeds the attractive force joining the molecules together pulling them apart and creating cavitation bubbles. These bubbles grow through coalescence and later collapse during compression phase creating hot spot and extreme local condition. The temperature may reach up to 5000 K and pressure increase may be up to 1000 atm. These hot spot expedite the biochemical reactions in its vicinity [14,76,15,1,69,91].

Acoustic cavitation is the main mechanism involved in the ultrasound assisted extraction. The collapsing cavitation bubbles and the sound waves may induce either one or combination of the phenomena such as fragmentation, localised erosion, pore formation, shear force, increased absorption and swelling index in the cellular matrix of the plant. The collapsing cavitations bubbles generate shockwaves and accelerated inter-particle collision causes the fragmentation in cellular structure. The rapid fragmentation leads to solubilisation of the bioactive component in the solvent due to decrease in particle size, increased surface area and high mass transfer rates in the boundary layer of solid matrix [70,41]. Ultrasound leads to the localized damage to the plant tissues termed as erosion. This erosion may also be attributed to the implosion of the cavitation bubbles on the surface of plant tissues. The eroded part facilitates the contact of solvent, increasing the yield of extraction [60]. The formation of pores during cavitation, a phenomena knows as 'sonoporation', in the cell membranes results in the release of the bioactive compounds present in cell [51,21,5]. In addition to that, the generation and collapse of cavitation bubbles induces shear force and turbulence within the fluid which results in breakdown of the cell walls contributing to releasing the bioactive compound [2,1,5,80]. Ultrasound increases the water absorption of the pomace thereby enhancing the accessibility of the water as solvent to the bioactive compounds to be extracted along with increased diffusivity of the bioactive compounds itself [61]. Ultrasound also increases the swelling index of plant tissue matrix which helps in both desorption and diffusion of solutes resulting in increased extraction [27]. The increase in the extraction yield by UAE can't be attributed to a single mechanism but due to the combined effect of all the mechanism.

## 3. Ultrasonic system

In general UAE has been performed using ultrasonic bath and ultrasonic probe, which are based on piezoelectric transducer as source of ultrasound power. In ultrasonic bath the solid matrix are dispersed in the solvent in a stainless steel tank connected to transducer. Ultrasonic bath are more economical and easy to handle, but its low reproducibility restrict its use in extraction process. Ultrasonic probe consist of a probe or horn connected to a transducer. The probe is immersed in extraction vessel and delivers ultrasound in the media with minimum energy loss. The probe based systems are commonly preferred compared to bath system due to the higher ultrasonic intensity (tip of the probe) and used as a powerful tool for the extraction of bioactive compounds [14]; The non-uniform energy distribution and reduction of power with time reduces the efficiency of bath system as compared to probe system. In probe system, the energy delivered is concentrated in a specific sample zone generating more efficient cavitation effect [1].

The ultrasonic energy is radiated into the sample through probe. Probe of smaller diameter tip generate greater cavitation effect but the effect is constricted to narrower field. Probes of larger diameter tip has low cavitation effect but the energy is distributed to larger area. The commercially available laboratory scale probe tip diameter varies from 2 mm for handling sample volume upto 5 mL to 25 mm to handle sample upto 1L volume. 20 mm flat tip probe were used for the extraction of pectin from pomegranate peel [54], jackfruit peel [53], polysaccharide from rambutan peel [46]. Xu et al. [87] used probes of 13 mm and 25 mm to extract pectin from grapefruit peel.

## 4. Factors contributing to UAE

### 4.1. Ultrasonic power

Power delivered during UAE has also been expressed as amplitude percentage in the range 0 to 100% where 100% amplitude indicates the rated power of the equipment [56] and power density ( $\text{W.mL}^{-1}$ ) which is calculated as power dissipated per unit volume of the extraction medium. It has also been shown that there exist a linear relationship between ultrasonic amplitude and the output power when the amplitude ranged from 30% to 80% of the maximum power [87]. The power applied for UAE of bioactives from fruit and vegetables by-products depend upon the compound to be extracted and the types of plant matrix selected for the extraction and varied in the range from 20 to 700 W [90,75].

The yield of the UAE extraction increases with increase in power or power density and then decreases after reaching a peak [18,46,64,65,85,87]. This can be explained by the increase in the effect of violent cavitation bubbles collapse by increase in power. The resonant bubble size is proportional to the power of the ultrasonic wave and as the bubble size increases their impact on implosion also intensifies. This provokes fragmentation, pore formation and mixing in the tissue increasing the diffusivity and enhanced extraction yield [46]. The other related phenomenon which has been given to explain increase in yield is that mechanical vibration of ultrasound probe results in increased contact area between solid and solvent which increases the penetration of solvent. The hydrodynamic force also increases with increase in power resulting in disruption of tissues [75]. However when power increased to very high level it leads to increase in the number of bubble formed. The cavitation effect is decreased at higher bubble volume concentration. Increased number of bubbles leads to a large inter-bubble collision, deformation and collapse in nonspherical way which decreases the impact of the bubble implosion [28]. In addition to that the layer of cavitation bubbles assembled around the probe tip, hinders the transmission of the energy into the extraction medium (saturation effect), reduces the yield [20]. The high ultrasound intensity may also degrade the bioactive compound decreasing the yield.

Al-Dhabi et al. [3] studied the interactive effect of power with

temperature and sonication time in waste spent coffee grounds and found that increase in power from 100 to 200 W increased the yield of the total phenolic compound and when the power was increased above 250 W the yield decreased. Whereas, linear effect of power on the yield of phenolic, total flavonoid and total antioxidant has also been reported by González-Centeno et al. [33]. The effect of power on the yield also depends upon other extraction parameters such as temperature, time and pH of the extracting solvent. Palma and Barroso, [56] reported the effect of power depended on the temperature applied on the extraction of malic acid and tartaric acid from grape seed. At high temperature (50 °C) the increase in power increased the yield while at low temperature (20 °C) increase in power increased the yield. In the extraction of pectin from eggplant peel the effect of power on yield was shown to be dependent on time. When the time of processing was less, the yield increased with increase in power while at longer duration of ultrasound treatment the yield decreased with increase in power [39]. The antioxidant yield increases with increase in power though their activity decreased as found in extraction of antioxidant from pomegranate peel [58].

#### 4.2. Frequency of ultrasonic

The frequency used in UAE of bioactive compounds from fruit and vegetable by-products lies between 20 and 120 kHz. Low frequency high intensity ultrasound generates strong shear and mechanical force desirable in extraction process while high frequency low power density produces large number of reactive radicals. There are very few studies on the effect of varying frequency on the extraction yield and quality, and most of the studies were focused on constant frequency. A constant frequency of 20 kHz has been applied for extraction of pectin from pomegranate peel [54]), passion fruit peel [29], mango peel [36], orange peel [37], sisal waste [47], grapefruit peel [85] and antioxidant from pomegranate peel [58], and 24 kHz for malic and tartaric acid extraction from grape seed [56]. A selected frequency from 30 to 40 kHz range has been applied on grape by-product for anthocyanin extraction [22], tomato waste for pectin extraction [35], grape pomace for pectin [52], papaya seed for oil [75]. Selection of constant low frequency might be due to the concept of formation of less number of cavitation bubbles with larger diameter favouring large cavitation effect which decreases with increase in ultrasound frequency [42]. Cavitation bubbles requires a certain minimum duration of compression-rarefaction cycle to form and grow and if this cycle is too short, the cavitation bubble will not be induced and grow. Ultrasonic frequency and duration of rarefaction phase are inversely proportional to each other; hence, at high frequency cavitation bubble gets very short time to grow which impedes their implosion effect. The large number of bubbles formed at high frequency offer more resistance to mass transfer [49,50].

The effect of varying frequency (19, 25, 40 and 300 kHz) on the UAE of vegetable oil from soyabean germ was analyzed by Cravotto et al. [24] with the conclusion that best yield was obtained at 19 kHz. Similarly the effect of varying the frequency (40 kHz, 80 kHz and 120 kHz) on extraction of phenolics from grape pomace was investigated by González-Centeno et al. [33] using the response surface methodology with the conclusion that 40 kHz was most effective. Frequency showed quadratic effect on studied response such as total phenolic content, total flavonoid content and total antioxidant activity. At low and high frequency the yield was high while in the intermediate frequency range the yield was low for the all the studied responses.

#### 4.3. Duty cycle of ultrasonication

Duty cycle is the ratio of pulse duration and cycle time of ultrasonic wave, expressed in percentage. Pulse duration is the time for which ultrasonic transducer remains "on" while pulse interval refers to the time for which ultrasonic transducer remains "off". The sum of pulse

duration' and 'pulse interval is known as 'cycle time'. The effect of varying duty cycle (DC) on the UAE has been studied by Pan et al. [58] in pomegranate peel and Xu et al. [87] on grapefruit peel in the form of pulsed ultrasound assisted extraction (PUAE). Pan et al. [58] concluded that though there was not much difference in the yield and time of extraction in PUAE but the saving of electrical energy in PUAE was 50% more as compared to continuous UAE. Xu et al. [87] observed that pectin yield from grapefruit peel first increased with increase in DC and then decreased after reaching a peak of 50%. At low DC for example 33% the total sonication time (20 sec) remains very short per minute of operation and insufficient to cause the fragmentation of tissue for extraction of solute. At high DC (50–70%) the cavitation effect decreases due to saturation effect and inter-bubble collision as discussed in effect of power. The ultrasound operated in pulsed mode decreases the number of cavitation bubble but increases the intensity of bubble implosion. An increase in yield at 80% DC was explained by negation of saturation effect and inter-bubble collision by longer sonication time (48 s).

#### 4.4. Solvent used in ultrasonic extraction

Different solvents i.e. acidified water, ethanol, alcohols, acetone, water etc. have been used for the extraction of different compounds during UAE. The solvent used for the UAE of pectin is acidified water. The acidification of water has been done either through mineral acid or through citric acid. The mineral acid that has been used to change the pH of distilled water and evaluate its effect on pectin extraction includes hydrochloric acid (for grapefruit peel, durian rind), nitric acid (for passion fruit peel, mango peel). Citric acid has been used in grape pomace, banana peel, orange peel and sunflower head for UAE of pectin. Minjares-Fuentes et al. [52] and Maran et al. [48] used citric acid instead of mineral acid for the extraction of pectin from grape pomace and banana peel, respectively and reported that combination of citric acid and ultrasound is highly efficient for the extraction of pectin.

Alcohols and acetone, with different levels of water, have been widely used to extract phenolic compounds from plant materials. Ethanol has been found to possess the highest affinity for phenolics in many investigated systems and hence it is the first choice for the extraction of phenolic compounds from fruit and vegetable waste [64]. The other reasons due to which ethanol is used as preferred solvent is its affordability, its origination from a renewable source (sugar cane) and its categorization as GRAS (generally recognized as safe) solvent [67]. The concentration of ethanol is one of the most important factors affecting the yield in UAE. While the target is to eliminate the ethanol use in the extraction but the current research has only been able to reduce its volume for extraction using UAE. González-Centeno et al., [33] used water for the extraction of phenolic, flavonoids and antioxidant compounds from grape pomace and observed that aqueous-UAE was able to extract 12% to 38% of phenolic compounds from grape pomace achieved by organic UAE. This indicates that we are still very far from achieving the desired target of complete elimination of organic solvent in extraction and propels for further investigation in this field.

Increase in ethanol concentration increases the yield of phenolic compound until a maximum ethanol concentration and then it has negative effect on the yield. This trend has been observed in extraction of flavonoids from grapefruit solid waste [31], hawthorn seed [57], cyanidin-3-O-glucoside extraction from jaboticaba peel [67]. This variable trend might be due to the increase in solubility and diffusivity of the phenolic compound due to the decrease in dielectric constant of solvent with increase in ethanol concentration. The ethanol concentration near 100% i.e. highly pure ethanol solvent causes dehydration of the tissue of plant along with denaturation of the protein leading to decreased yield at such high concentration.

Contrary to above trend the increase in ethanol concentration at fixed temperature and extraction time increased the yield of total phenolic compound from grape seed and reached maximum at the

maximum ethanol concentration [32]. Similarly, Rodrigues et al. [67] observed positive linear effect of ethanol concentration on the extraction of monomeric anthocyanin and phenolic compound from jabuticaba peel. They also showed through the Pareto chart of the standardized effect that linear term of ethanol concentration had maximum effect on the extraction of monomeric anthocyanin, phenolic compound, cyaniding-3-O-glucoside and ellagic acid from jabuticaba peel.

#### 4.5. Liquid (Solvent) to solid ratio (LSR)

The concentration of solvent has been expressed either as liquid solid ratio (LSR) which is ratio of volume of solvent (mL) to quantity of sample taken for extraction (g) or the solid liquid ratio (SLR) which is the reciprocal of LSR. The yield of UAE increases with increase in LSR up to certain point and then decreases after reaching a peak. At low LSR, the viscosity of the solution is high which poses more difficulty in cavitation effect as the negative pressure in the rarefaction cycle has to overcome a stronger cohesive force in the high viscous solution. With the initial increase of LSR, the viscosity and concentration of extraction medium decrease which leads to greater cavitation effect. The higher concentration difference of the solute increases the diffusivity and dissolution of the solute in the solvent augmenting the extraction process. At high LSR the ultrasound intensity imposed on the by-product matrix is higher causing more fragmentation, erosion and pore formation effect thereby increasing the yield. The increase in the contact area between material and solvent may also increase the yield. The decrease in the yield at very high LSR can also be attributed to the enhanced cavitation effect resulting in degradation of the desirable solute itself [46,75,87]. Pectin yield from the sisal waste increased when the LSR increased from 20:1 to 30:1 and thereafter decreased when LSR was further increased to 40:1 [47]. Similar trend has been reported for extraction of pectin from grapefruit peel [87], oil from papaya seed [75], polysaccharides from the stem of *Trapa quadrispinosa* (sijiaoling stem) [65], rambutan fruit peel [46]. Moorthy et al. [54] reported increase in pectin yield from pomegranate peel as LSR increased from 10:1 to 15:1 and the further increase in LSR to 20:1 decreased the pectin yield.

The deviations from above trend have been reported for the extraction of phenolic, polysaccharide xylan and malic acid. Rodrigues et al. [68] reported increase in yield of phenolic compounds from coconut (*Cocos nucifera*) shell powder when LSR increased from 20:1 to 50:1. Similarly Chen et al. [18] reported increase in yield when LSR increased from 5:1 to 15:1 for the extraction of polysaccharide from litchi seed. Hromadkova et al. [95] reported that yield of both the total extracted xylan and immunogenic water-soluble xylan decreased with decreasing LSR. Palma et al. [56] reported that volume of the extracting liquid has no effect on the extraction of tartaric acid from grape seed while the recovery of the malic acid increased with increase in solvent volume at 50 °C. At 20 °C increase in solvent volume was shown to have adverse effect on the yield.

#### 4.6. Temperature of UAE

The increase in temperature initially increases the yield of UAE and further increase in temperature decreases the yield, similar to the effect caused by increase in power. The increase in temperature increases the UAE yield due to dual effect on solute and solvent both. Temperature increase on the one hand increases the desorption property and solubility of the solute in the solvent while on another hand it decreases the viscosity of the solvent itself which leads to the increased diffusivity of the solvent in the tissue matrix. The further increase in temperature decreases the yield due to weakened cavitation effect. This trend has been observed by Al-Dhabi et al. [33] in extraction of phenolic compound from waste spent coffee grounds by UAE where the yield increased with the increase in temperature from 30 °C to 45 °C and beyond 45 °C the yield decreased. Similar trend has been reported for extraction of flavonoids from hawthorn seed [57], pectin from

pomegranate peel [54]), grapefruit peel [87], polysaccharide from rambutan fruit peel [46], antioxidant polysaccharide from sijiaoling stem [65]).

The effect of higher temperature UAE operation on the yield of the bioactive components has been explained by different hypothesis. One hypothesis says that at high temperature the increased vapour pressure of the solvent occupies the cavitation bubble formed during rarefaction cycle, due to which the pressure gradient between inside and outside the bubble is reduced. So, even though the number of cavitation bubbles is large at high temperature they implode with less intensity causing lesser damage to the cell decreasing the yield. While the second hypothesis says that due to large number of cavitation bubbles formed at higher temperature and upon their subsequent collapse, the increased shear stress causes the degradation of the desired component. The third hypothesis considers reduction of surface tension of solvent at higher temperature as the main cause for decrease in the intensity of collapse of the cavitation bubble effectively decreasing the mass transfer of the component to be extracted [90,6]. Increase in yield with increase in temperature without dip at higher temperature has also been reported by different researchers. Ghafoor et al., [32] reported that total phenolic compound from grape seed increased with temperature with maximum yield obtained at highest temperature tested. Similar trend was observed by Ramic et al. [64] for total phenolic compound in black chokeberry waste, Rodrigues et al. [68] for phenolic compounds from coconut (*Cocos nucifera*) shell powder, Minjares-Fuentes et al. [52] for extraction of pectin from grape pomace.

#### 4.7. pH of solvent

pH is an important factor affecting the extraction yield and properties of bioactive compound during UAE. The extraction of polysaccharides (pectin) from the fruit and vegetable by-products has been studied in the pH range of 1–5. The recovery of pectin is high when the pH maintained is low. The high acidic medium improves the cell wall fragmentation, hydrolyses the insoluble pectin into soluble form and reduces the molecular weight of pectin increasing their dissolution into the surrounding medium and thus enhancing their recovery. At high pH value, pectin aggregates and which restricts their release into the extraction medium. The optimum pH reported for the extraction of pectin from pomegranate peel [54] is 1.2, from orange peel [37], eggplant peel [39], jackfruit peel [53] is ~1.5, from, and from banana peel and sunflower head [62] is 3.2.

pH has also been reported to exhibit maximum effect among the studied extraction variables for example in extraction of pectin from grape pomace and orange peel [52,37]. Minjares-Fuentes et al. [52] reported linear effect of pH on the molecular weight of extracted pectin. pH also effects the degree of esterification (DE) of extracted pectin. At low pH, DE is low which is due to deesterification of pectin in the high acidic condition. However, it is interesting to note that effect of pH on DE was reported differently on UAE of pectin from grape pomace and orange peel. Grape pomace DE increased on decreasing the pH and opposite trend was found for orange peel. This may be due to the interactive effect of other variables such as temperature, power and time with pH.

The effect of pH on extraction of phenolic compounds has not been much reported. Rodrigues et al. [68] studied the effect of pH range 4.5–6.5 of ethanol solvent adjusted by HCl on the extraction yield of phenolic compound from coconut shell powder and observed positive linear effect with maximum yield at pH 6.5. Rodrigues et al. [67] found significant quadratic and negative effect of pH on the extraction of monomeric anthocyanin from jabuticaba peels which meant that increase in pH favoured the monomeric anthocyanin extraction upto certain value and thereafter further increase in pH decreased the monomeric anthocyanin yield. The linear and quadratic effect of pH on total phenolic content was also significant with the conclusion that the optimum pH for the extraction lies in the range of 1–3.



**Table 1**

Optimized extraction condition for ultrasound assisted extraction of pectin from fruit and vegetable by-products.

| Bioactive | Waste part         | Extraction Variables  | Operating condition Constants and solvent Used   | Optimum Condition for UAE/<br>Major Findings                         | Yield (%) | References |
|-----------|--------------------|---|--|--|-----------|------------|
| Pectin    | Pomegranate peel   | T:50–70; t:15–35; pH:1–2;<br>LSR:10:1–20:1                                    | P:130 W; F:20; S:Citric acid solution  | T:61.9; t:28.31; pH:1.2; LSR:17:1                                    | 23.87     | [54]       |
|           | Grape pomace       | T:35–75; t: 20–60; pH:1–2   | P:140 W, 0.05 W.mL <sup>-1</sup> ;<br>F:37; S:Citric acid solution                                 | T:75; t:60; pH:2   | 32.3      | [52]       |
|           | Tomato waste       | T:60 & 80; t:15–90  | F:37; S:Ammonium oxalate (16 g/L)/<br>oxalic acid (4 g/L)  | t: 15 min.   | 35.7      | [35]       |
|           | Grapefruit peel    | T:60–80; t: 4–30  | F:24; P200 W; pH:1.5; S: Acidified<br>water 0.1 N HCl:   | T:70; t:25   | 17.92     | [6]        |
|           | Grapefruit peel    | P:0.2–0.53 W.mL <sup>-1</sup> ; T:30–80; t: 10–60;<br>LSR:30:1–70:1; DC:33–80 | F:20; pH:1.5; S:0.5 M Hydrochloric acid  | P:0.4 W.mL <sup>-1</sup> ; T:60; LSR:50:1;<br>DC:50                  | 18.11     | [87]       |
|           | Grapefruit peel    | P:10.18–14.26 W.cm <sup>-2</sup> ; T:60–80; t:20–40                           | F:20; DC:50; pH :1.5; S:0.5 M<br>Hydrochloric acid   | P:12.56 W.cm <sup>-2</sup> T; 66.71; t:27.95                         | 27.34     | [85]       |
|           | Grapefruit peel    | Particle size of peel:<br>From less than 0.18 mm to > 10 mm                   | F:20; DC:50; pH:1.5; S:0.5 M<br>Hydrochloric acid; T:66.71; t:27.95;<br>P:12.56 W.cm <sup>-2</sup> | Particle size: 0.9 mm  | 23.4      | [94]       |
|           | Passion Fruit peel | t:3–20  | P:664 W.cm <sup>-2</sup> ; F:20;<br>LSR:30:1; pH:2; S:1M nitric acid                               | t:10   | 12.67     | [29]       |
|           |                    | P:132.8–664; T:45–85  | t:10; F:20; LSR:30:1; pH:2; S:1M nitric<br>acid  | T:85; P:664  |           |            |
|           | Banana peel        | P:100–500 W; t:5–45; pH:1–5;<br>LSR:5:1–25:1                                  | F:20; S:Citric acid Solution   | P: 323; t:27; pH:3.2; LSR:15:1                                       | 8.99      | [48]       |
|           | Mango peel         | NA  | T:85; t:10; P:497.4 W.cm <sup>-2</sup><br>F:20; S:1M nitric acid                                   | Yield of UAE pectin 50% more<br>than chemical extraction             | 8.6       | [36]       |
|           | Orange peel        | P:50–150; t:10–30; pH:1.5–3   | F = 20; LSR:20:1; S:Citric acid solution   | P:150; t:10; pH:1.5  | 28.07     | [37]       |
|           | Eggplant peel      | P:50–150; t:10–30; pH:1.5–3; LSR:15–40  | S: Acidified water   | P:50; t:30; pH:1.5; LSR:20   | 33.64     | [39]       |
|           | Jackfruit peel     | T:50–70; t:15–30; pH:1–2;<br>LSR:10:1–20:1                                    | P:130 W; F:20; S:Citric acid solution  | T:60; t:24; pH:1.6; LSR:15:1   | 14.5      | [53]       |
|           | Sunflower head     | P:150–550; t:10–50; pH:1–5;<br>LSR:5:1–25:1                                   | F:20; S:citric acid solution   | P:375; t:32; pH:3.2; LSR:15:1  | 8.89      | [62]       |
|           | Durian Rind        | T:80–90; t:60–240; pH:2–2.5;  | LSR:9:1; S:1N HCl Acidified water  | T:85; t:240; pH:2.3 for max. yield<br>T:85; t:60; pH:2.2 for max. DE | 8.8       | [82]       |

(Where, T = Temperature (°C), t = Sonication Time (min), P = Power (W)/Power intensity (W.cm<sup>-2</sup>)/Power density (W.mL<sup>-1</sup>)/Amplitude (%); F = Frequency (kHz), LSR = Liquid Solid Ratio (mL.g<sup>-1</sup>), DC = Duty cycle (%), EC = Ethanol Concentration (%), S = Solvent, NA: Not available).

#### 4.8. Time of UAE

The effect of UAE time on the yield of bioactive compounds from fruit and vegetable by-products has been extensively explored and reported. Increase in sonication time increases the yield initially and thereafter the yield decreases on further increment in time, the effect is similar to increase in power and temperature. Upon the initial increase in sonication time, the cavitation effect of the ultrasound enhanced the swelling, hydration, fragmentation and pore formation of the plant tissue matrix from where the solute is to be extracted. All these factors increase the exposure of the solute and the extraction medium and help their release into the solvent. The exposure of ultrasound for very long duration causes structural damage to the solute and decreases the extraction yield. This trend has been reported for antioxidant polysaccharide extraction from *T. quadrispinosa* (sijialing stem) [65], pectin extraction from pomegranate peel [54], jackfruit peel [53], sunflower head [62], banana peel [48], grapefruit peel [85], rambutan fruit peels [46], phenolic compound extraction from waste spent coffee grounds [3], phenolic compounds from black chokeberry waste [64] and flavonoids compounds from hawthorn seed [57].

Positive linier effect of time on the UAE yield has also been reported for pectin from eggplant peel [39], grape pomace [52], phenolic compound from grape pomace [33], grape seed [32], phenolic compound and anthocyanin from jabuticaba peel [67], total flavonoids and antioxidant activity from grape pomace [33], flavonoid from hawthorn seed [57]. Whereas the negative linear effect of time on yield has been reported for pectin from sour orange peel [37], phenolic compounds from coconut (*Cocos nucifera*) shell powder in the time range 20–60 min [68]. For the extraction of oil from papaya seed the yield increased with time at high temperature and high solvent to solid ratio [75]. For the extraction of pectin the optimized sonication time has been reported in the range 10–60 min while for extraction of phenolic

compounds it has been 10–90 min varying for different fruit and vegetable by-product.

#### 5. Pretreatment for UAE of bioactive compounds

Pretreatment of fruits and vegetable waste play an important role in the yield of UAE of bioactive compounds. For UAE of pectin and polysaccharide from fruits and vegetables by-products, the raw materials are subjected to pretreatment such as blanching, drying and milling. The blanching is carried out by immersing the by-products at 80 °C–100 °C for 3–5 min followed by cooling in ice bath to inactivate the enzymes [87,85,29]. The drying is carried out in hot air oven at temperature range 45 °C–60 °C for 24–72 h until the sample reaches a constant weight [37,48,54]. The dried peels are milled using electric grinder to obtain fine particles having diameter less than 0.25 mm. For the UAE of antioxidant crude polysaccharides, phenolic compounds and dietary fibers the fruits and vegetables by-products may be defatted using before drying and milling. Raza et al. [65]), for the UAE of antioxidant crude polysaccharides degreased the sijialing stem with petroleum ether for 12 h in Soxhlet apparatus and thereafter washed them with 95% ethanol for 6 h to remove some colored materials, monosaccharide, oligosaccharides and some small molecule materials before drying. Similarly, Al-Dhabi et al. [3]) for the extraction of phenolic compounds from Spent coffee ground used Soxhlet extraction system with petroleum ether to defat the samples. Begum and Deka [10] deoiled banana bract using n-hexane, stirring them at 150 rpm for 15 min thereafter centrifuging the sample at 4000 rpm for 20 and finally drying at 50 °C.

## 6. Application of UAE in extraction of bioactive compounds from fruit and vegetable by-products

### 6.1. UAE extraction of pectin

The presence of pectin in the cell wall and middle lamella of many plants including fruits and vegetables have encouraged researchers to exploit waste peel, pomace and rind of the plant for the UAE of pectin from them. Peel of fruits such as pomegranate [54], orange [37], banana [48], grapefruit [6,85,87,94], mango [36], passion fruit [29], vegetables such as eggplant [39], jackfruit [53] and other parts such as tomato waste [35], grape pomace [52], sunflower head [62] and durian rind [82] has been used to extract pectin.

Pectin yield above 25% through UAE have been obtained from pomegranate peel, grape pomace, tomato waste, grapefruit peel, orange peel and eggplant peel. The optimized condition for the UAE of pectin from different plant by-product is given in Table 1. The yield of pectin depends on ultrasonic parameters such as frequency, power, duty cycle, power intensity, sonication time and extraction variables such as temperature, LSR, pH of solvent either alone or their interactive effect. The increase in yield and reduction of extraction time of pectin through UAE has been established through several findings. Wang et al. [85,86] compared chemical extraction with UAE of pectin from grapefruit peel and reported the higher yield (16.34%) and reduction in the extraction time by 37.78% using UAE. Similarly Oliveira et al. [29] reported 1.6-fold increase in the pectin yield on UAE of passion fruit peel as compared to chemical extraction. Guandalini, et al. [36] carried the UAE of pectin from the residue of phenolic compound extracted mango peel and observed 50% increase in yield (from 5.61 to 8.6) while the yield of UAE pectin from rehydrated mango peel increased by 31% (from 6.2 to 8.1) as compared to pectin extraction without ultrasound without affecting quality of pectin. Grassino et al. [35] noted that pectin extracted at 60 °C through conventional extraction gave highest yield but the quality of the pectin obtained through 15 min UAE was better. For extraction at 80 °C the yield of pectin obtained through 24 h conventional extraction and 15 min UAE were identical concluding very clearly the shortening of extraction procedure through UAE. The characterisation of extracted pectin through UAE has been done to ascertain their quality and establish their properties. High methoxyl pectin (Degree of esterification > 50%) has been extracted using ultrasound from eggplant peel, grape pomace, passion fruit peel, sunflower head, and grapefruit peel (Table 2).

Hosseini et al. [37] and Kazemi et al. [39] carried the characterisation of pectin extracted from sour orange peel and egg plant, respectively. Wang et al. [94] studied the effect of particle size on two-stage extraction of pectin from grapefruit peel. They reported that material particle size of 0.9 mm was sufficient to achieve an optimal yield for UAE. In the first stage the UAE was carried at fixed ultrasonic parameters with varying particle size and pectin was extracted. It was found that after first stage extraction, the grapefruit peel residue still had approximately 20% pectin left in it. In the second stage the pectin extracted in first stage was diluted with distilled warm water, stirred, cooled and centrifuged to obtain the second stage pectin. The incomplete extraction of pectin in first stage was attributed to the 'barrier effect' due to increase in viscosity of the extraction mixture owing to increase in pectin concentration in the mixture solution at the later period of first stage extraction. The addition of water in the second stage helped to dissolve the remaining pectin increasing the yield. Xu et al. [87] mentioned about the high correlation between pectin yield and tissue swelling and concluded that disruption of vegetal tissue by ultrasonic treatment is the main mechanism involved in the improvement of extractability through UAE.

### 6.2. Polysaccharides

Polysaccharides present in various plant tissues have been

**Table 2**  
Optimized extraction condition for ultrasound assisted extraction of dietary fiber, polysaccharide, tartaric acid, malic acid and carotenoids from fruit and vegetable by-products.

| Bioactive               | Waste part                         | Operating condition Constants and solvent Used  | Extraction Variables  | Optimum Condition for UAE/Major Findings   | Yield (%)    | References |
|-------------------------|------------------------------------|---|---|--|--------------|------------|
| Dietary Fiber           | Banana bract                       | F:20; S:NaOH Solution                           | P:20–50%; T:60–80; t:10–20; LSR:15:1–25:1   | P:50%; T:80; t:10; LSR:25:1  | 71           | [10]       |
|                         | Asparagus stem                     | F:25; T: 25; t:60 S:Water                       | NA  | NA   | 66           | [38]       |
|                         | Papaya peel                        | T: 50; S:NaOH Solution                          | P:150–250; t:20–40; LSR:10–20   | P:175; t:30.76; LSR:16.55  | 37           | [89]       |
|                         | Citrus Changshan-huyou peels       | S:Sodium hexametaphosphate                      | P: 50–70 W; T: 60–80; t:15–25   | P: 60.28 W; T: 72.27; t:20.10  | 6.62         | [16]       |
| Polysaccharide          | Apple pomace                       | F:40;pH:2; LSR: 20:1; T: 80; S: Acidified water | P:200–500 W   | P:400 W; t:40  | 16.4         | [43]       |
|                         | Porso millet bran soybean residues | F:24; S:Water S: Alkali                         | P: 60–100%; t:5–20; P:250–500 W; T:30–80; t: 10–60; LSR: 10:1–60:1; AC:0.05–0.5 M | P:100%; t:9.3 P: 450 W; T:30;t: 10; LSR: 50:1 AC:0.05 M                                    | NA           | [25]       |
|                         | Rambutan peel                      | F:20; S:Water                                   | T:40–60; t:30–50; LSR:20:1–40:1   | P:110; T:53; t:41; LSR:32:1  | 8.3          | [46]       |
|                         | Litchi Seed                        | NA  | P:120–300 W; t: 05–45; LSR:05:1–15:1  | P: 222; t:45; LSR:15:1   | 3.23 mg GE/g | [18]       |
| Tartaric and Malic Acid | Corn cob                           | F:20; S:NaOH Solution                           | P:100–270; T:50–70; t:10–30; LSR: 10:1–25:1; AC:1 & 5%                            | Yield of ws-X was strongly affected by the alkali concentration and extraction temperature | 13.5–15.2    | [95]       |
|                         | Sijialing stem                     | F:40; S:Water                                   | P:120–200 W; T:30–70; t: 10–50; LSR:20:1–40:1                                     | P:160 W; T:58; t:4; LSR: 31.5:1  | 2.78         | [65]       |
|                         | Grape seed                         | F:24  | P:30 & 70%; T:20 & 50; t:5 & 15; Solvent: Water & Methanol                        | The most important variables were the extracting liquid and the extraction temperature     | NA           | [56]       |
|                         | Tomato pomaces                     | F:20  | T:25–45; t: 0–10; Pressure:0–100 kPa; Amplitude:58–94 µm; Hexane %25–75           | T:45;t:6; Pressure:50 kPa; Amplitude:94 µm; Hexane %58                                     | NA           | [96]       |

(Where, T = Temperature (°C), t = Sonication Time (min), P = Power (W)/Power intensity (W.cm<sup>-2</sup>)/Power density (W.mL<sup>-1</sup>)/Amplitude (%), F = Frequency (kHz), LSR = Liquid Solid Ratio (mL.g<sup>-1</sup>), DC = Duty cycle (%), AC = Alkali Concentration, S = Solvent; NA: Not available).

confirmed with various bioactivities such as antioxidation, immunomodulation, anti-tumor and hypoglycemic activity. The healing capacity and low toxicity properties make them a favourable functional food. Various unutilized plants parts are rich in polysaccharides and have been explored for their extraction by UAE. Chen et al. [18] extracted water-soluble polysaccharides from litchi seed and optimized the UAE condition (Table 2). The structural characteristics and bioactivity including antioxidant activity were confirmed in the extracted polysaccharide by UAE. Hromadkova et al. [95] isolated the xylan component of corn cobs in polymeric form and concluded that UAE shortened the extraction time and lowered the alkali requirement and extraction temperature. The sugar composition and main structural features of xylan extracted through UAE were same and biological activity higher as compared to xylan extracted without ultrasound treatment in 5% NaOH solution. Maran and Priya [46] extracted polysaccharide from rambutan fruit peel and determined the optimum condition for extraction as LSR 32:1 mL g<sup>-1</sup>, ultrasonic power of 110 W, extraction temperature of 53 °C and extraction time of 41 min. Raza et al. [65] used sijaoling stem to extract antioxidant polysaccharide and found that polysaccharide obtained by UAE showed higher DPPH, ABTS radical scavenging activity and stronger reducing power, total antioxidant capacity compared with polysaccharide obtained by hot water extraction.

### 6.3. Dietary fibers

Dietary fibers is composed of carbohydrate polymer with some non-carbohydrate component exhibiting health benefit such as prevention of diabetes, coronary heart diseases, strokes, hypertension, obesity, and certain gastrointestinal cancer. They are abundantly found in fruit and vegetable by-products and UAE has found to increase their extraction efficiency from the plant matrices. UAE of dietary fiber from *Citrus Changshan-huyou* peels [16] and apple pomace [43] shows better yield, consumed less time and required low temperature as compared to conventional solvent extraction. Similarly, UAE of dietary fiber from culinary banana bract, papaya peel and soyabean residue exhibited higher yield, purity, thermal stability, water-holding, oil-holding and swelling capacities than alkaline extracted dietary fiber [89,10,78]. UAE dietary fiber contained higher percentages of essential amino acids and essential trace elements while the crystallinity less than alkaline dietary fiber. Iwassa et al. [38] found that fiber concentrate obtained by ultrasound from asparagus stem had the best proportion of soluble fiber to insoluble fiber and antioxidant potential similar to the control. The optimized condition for the UAE of dietary fibers from different plant by-product is given in Table 2.

### 6.4. Polyphenols

Extraction of phenolic and antioxidant compound are another major stress area where researchers have used UAE. Phenolic compounds and antioxidant compounds has been extracted from mango peel [36], pomegranate peel [58], jabuticaba peels [67], grape pomace [33], fermented grape pomace [9], grape by-product [22], grape seed [32], hawthorn seed [57], grapefruit solid waste [31], black chokeberry by-products [26,64], coconut shell powder [66,68] and spent coffee ground [3]. The optimized condition for the UAE of polyphenols from different plant by-product is given in Table 3.

UAE of polyphenols have been studied with respect to difference in temperature, solvent concentration, frequency and time of extraction. Pan et al. [57] investigated the effect of different ultrasonic parameters on extraction of flavonoids compound (FC) from hawthorn seed. Ultrasonic time, ethanol concentration and extraction temperature were identified as the most significant variables influencing the extraction yield of FC while ultrasound temperature, solid-liquid ratio and extraction time did not exhibited significant effect on FC extraction. Garcia-Castello et al. [31] extracted flavonoid compounds from

grapefruit solid waste using UAE and reported that naringin was most abundant flavonoid in the extract ranging from 24 to 36 mg/g dry weight. They found that main factors affecting the total phenolic content and total antioxidant activity of the extract is ethanol concentration. Total phenolic content (TPA) and total antioxidant activity (TAA) was 50% and 66% higher in UAE extraction as compared to conventional solid-liquid extraction. They also reported that UAE carried free of organic solvent (0% ethanol concentration) yield similar TPC and TAA. Ghafoor et al. [32] reported that the antioxidant activity of grape seed was significantly affected by linear and quadratic term of ethanol concentration, extraction temperature and extraction time. Hence, it can be concluded that the extraction time was highly significant factor for the extraction of phenolic compounds and antioxidants [32].

Corrales et al. [22] extracted phenolic compounds and anthocyanin from grapes by-products (skins, stems and seeds) at ultrasound frequency of 35 kHz (70 °C & 1h) and concludes that UAE increased the phenolic extraction by two fold while there was no significant difference in the extraction of anthocyanin as compared to control. Opposite to that the Guandalini, et al. [36] reported that the UAE did not affect the extraction yield of phenolic compound from mango peel. That shows that the effect of ultrasonication on extraction of phenolic compounds also depends on source of phenols. Al-Dhabi et al. [3] and d'Alessandro et al. [26] used UAE for the extraction on phenolic compounds from waste spent coffee grounds and black chokeberry waste respectively and reported the optimized UAE parameters for the higher yield. d'Alessandro et al. [26] proposed a mathematical model based on Peleg equation and suggested different optimum parameters based on the objective of the extraction. For minimizing the extraction time for obtaining 90% of the extractable anthocyanin, the optimum condition suggested was 70 °C temperature, 34% ethanol concentration, 100 W power and 17 min time. For obtaining 90% of the extractable anthocyanin in water (aqueous extraction), the optimum condition suggested was 100 W power for 38 min at 70 °C temperature using UAE and 48 min without using UAE, a 20% reduction in time. For obtaining 90% of the extractable anthocyanin in water at 20 °C (aqueous extraction without heating), the optimum condition suggested was 100 W power for 55 min using UAE and 184 min without using UAE, more than three times reduction in time.

### 6.5. Oils

Recovery and yield of the oils can be increased by using UAE with the variation in the extraction time, frequency, temperature and power and there is a possibility to replace the harmful solvent used in chemical method. Cravotto et al. [23] extracted rice oil from different rice bran fractions using high intensity ultrasound at 18.2 kHz and 300 W (30 min). They reported that solvent hexane used for chemical extraction can be replaced by aqueous solution in UAE. Bran wax can also be hydrolyzed through sonication yielding policosanols. Cravotto et al. [24] carried out extraction of oil from soyabean germ using novel cavitation tube and immersion horn at different frequency and power. The best yield was observed in cavitation tube working at 19 kHz. On double sonication through inserting a immersion horn at 25 kHz in cavitation tube working at 19 kHz the extraction time reduced by half to 0.5 h. Assami et al. [97] extracted oil from caraway (*Carum carvi*) seed and reported 80% of essential oil recovery only after 30 min of UAE. Samaram, et al. [75] and Bimkr et al. [11] carried UAE of oil from papaya seed and winter melon seed, respectively. They reported the less antioxidant activity of UAE oil compared to Soxhlet method of extraction.

## 7. Experimental design and optimization

Response surface methodology (RSM) which is a collection of mathematical and statistical techniques has been employed to examine and optimize the variables of extraction process. Input variables such as

**Table 3**  
Optimized extraction condition for ultrasound assisted extraction of phenolic compounds from fruit and vegetable by-products.

| Bioactive                             | Waste part  | Operating condition                                    | Constants and solvent Used | Extraction Variables                                       | Optimum Condition for UAE/Major Findings  | References |
|---------------------------------------|---|--|----------------------------|--|---|------------|
| Phenolics/Flavonoids/<br>Antioxidants | Mango peel  | T:30; t:20; LSR:25:1; F:20; S: ethanol                 |                            | P:165.87 W.cm <sup>-2</sup> ; Ethanol % : 25–70            | The ultrasound did not affect the extraction of the total phenolics   | [36]       |
|                                       | Spent coffee ground                                 | F:20; S:ethanol  |                            | P:100–300 W; T:30–50; t: 05–45; LSR:5:1–30:1               | P:244 W; T:40; t: 40; LSR:17:1  | [3]        |
|                                       | Malta Peel  | F:20; S:ethanol  |                            | P:60–100%; t:15–35; LSR:20:1–40:1                          | P:70.89%; t:35; LSR:40:1  | [55]       |
|                                       | Grape pomace  | T:17 ± 3; LSR:5:1; S:Water                             |                            | P:50–150; t:5–25; F:40–120                                 | P:150; t:25; F:40   | [33]       |
|                                       | Grape seed  | F:40; P:250 W; S: ethanol                              |                            | T:40–60; t: 20–34; EC:40–60%                               | T:56.03; t: 29; EC:53.15 for max. TPC   | [32]       |
|                                       |   |  |                            |  | T:60.65; t: 30.58; EC:53.06 for max. antioxidant activity   |            |
|                                       |   |  |                            |  | T:55.13; t: 29.49; EC:52.35 for max. anthocyanins   |            |
|                                       | Grapefruit solid waste                              | F:40; P:100 W; S: ethanol                              |                            | T:34–61; t:15–48; EC:20–80 (g/100 g)                       | T:25; t: 55; EC:40 g/100 g  | [31]       |
|                                       | Hawthorn seed                                       | F:45; P:40 W; S: ethanol                               |                            | T:82–98; t: 30–50; EC:55–85%; LSR: 14:1–22:1               | T:91; t: 37; EC:72%; LSR:18:1   | [57]       |
|                                       | Black Chokeberry by-products from filer-tea factory | F:40; S: ethanol                                       |                            | P:72–216 W; T:30–70; t: 30–90                              | T:70; t:80; P:206 for total phenolics   | [64]       |
| Oil                                   |   |  |                            |  | T:70; t:75; P: 210 for flavonoids   |            |
|                                       |   |  |                            |  | T:70; t:45.6; P:216 for anthocyanins  |            |
|                                       |   |  |                            |  | T:70; t:89.7; P:199 for proanthocyanidins   |            |
|                                       | Black chokeberry waste                              | F:30.8; LSR: 40:1; S:ethanol                           |                            | T:20–70; t: 0–240; P:0–100 W; EC:0–50                      | High temperature and ethanol content in the solvent improved greatly the extraction yields.   | [26]       |
|                                       | Olive leaf extract                                  | F:50; T:25; S: ethanol                                 |                            | t: 20–60; EC:0–100%; LSR: 20:1–40:1                        | t:60; EC:50%; LSR: 20:1   | [73]       |
|                                       | Coconut (Cocos nucifera) shell powder               | F:25; P:150 W  |                            | Toasting temperature:100–200 °C<br>Toasting time:20–60 min |   | [66]       |
|                                       | coconut   | F:25; P:150 W; S:Ethanol                               |                            | T:30–60; t:20–60; pH:4.5–6.5; LSR:20:1–50:1                | Toasting temperature:100 °C<br>Toasting time:60 min   | [68]       |
|                                       | (Cocos nucifera) shell powder                       | F:25; P:150 W; T:30; LSR:20:1; S: ethanol              |                            | t:20–60; pH:2–5; EC:12–38                                  | T:30; t:15; pH:6.5; LSR:50:1  | [67]       |
|                                       | Jabuticaba peels                                    | Continuous UAE   |                            | P:2.4–59.2 W.cm <sup>-2</sup> ; t:2–90                     | t:10; pH:1; EC:46   | [58]       |
|                                       | Pomegranate peel                                    | T:25; F:20; LSR:50:1                                   |                            |  | Yield increased by 24% and time reduced by 90%  |            |
| Oil                                   |   | Pulsed UAE   |                            |  | Yield increased by 22% and time reduced by 87%  |            |
|                                       |   | T:25; F:20; LSR:50:1                                   |                            |  |   |            |
|                                       | Sage by-product                                     | F:40; LSR: 20:1; S:Ethanol                             |                            | P: 24–60 WL <sup>-1</sup> ; T:40–80; t:40–80               | P: 42.54 W/L; T:75.4; t:80;   | [88]       |
|                                       | Rice bran   | F:18.5; P:300; T: 45; t:30; LSR:12:1; S: NaOH Solution |                            | NA   | Oil extraction can be efficiently performed in 30 min under high-intensity ultrasound either with hexane or without any organic solvent | [23]       |
|                                       |   |  |                            |  | Best result in cavitation tube at 19 kHz  |            |
|                                       | Soyabean germ                                       | LSR:6.25:1; T:45                                       |                            | P: 60–80 W; F: 19.25, 40, 300;                             | T:52; P:325; t:36   | [24]       |
|                                       | Wintermelon seed                                    | F:20; LSR:1:10; S:Ethanol                              |                            | P:125–375 W; T:45–55; t:2040                               |   | [11]       |
|                                       | Papaya seeds  | F:40   |                            | P:235–700 W; T:25–50; t:5–30; LSR:6:1–10:1                 | P:700 W; T:62.5; t:38.0.5; LSR:7:1  | [75]       |

(Where, T = Temperature (°C), t = Sonication Time (min), P = Power (W)/Power intensity (W.cm<sup>-2</sup>)/Power density (W.mL<sup>-1</sup>)/Amplitude (%), F = Frequency (kHz), LSR = Liquid Solid Ratio (mL.g<sup>-1</sup>), DC = Duty cycle (%), EC = Ethanol Concentration (%), S = Solvent).



frequency, power, liquid solid ratio, temperature, time have been varied to study the potential influence on performance mainly the yield during the extraction process. Box-Behnken design (BBD) and central composite rotatable design (CCRD) are the two most commonly used RSM design used to conduct the experiment and optimize the extraction variables from different sources. Two factor two level ( $2^2$ ) and two factor three level ( $3^2$ ) full factorial design has also been used, but very less in number. BBD has been used for the extraction of pectin from pomegranate peel [54], grape pomace [52], grapefruit peel [85], eggplant peel [39], phenolic compound from spent coffee ground [3], grape pomace [33], hawthorn seed [57]. CCRD has been used for the extraction of pectin from banana peel [48], jackfruit peel [53], sunflower head [62],

Numerical optimization method has been adopted by most of the researchers to optimize the process variables for the extraction. Xu et al. [87] described a mathematical model for the extraction kinetics of pectin through which the time at which the pectin yield reached the maximum value can be determined. The developed model was also used to calculate the apparent activation energy ( $E_a$ ) of pectin dissolution and degradation from the logarithmic form of the Arrhenius equation.

## 8. Gap and future scope for research

The UAE of bioactive compounds from fruit and vegetable by-products offers huge advantage in terms of reduction in time, temperature, energy and chemicals requirement in extraction process. However, the complete elimination of chemical solvent in extraction with satisfactory yield needs to be achieved. Technological variations such as use of UAE as pretreatment and sequential extraction needs to be explored. The energy audit of UAE processes is required in future to compare the ultrasonic assisted processes with conventional and other novel techniques used for the extraction of bioactive component. The use of UAE in combination with other non-thermal extraction method such as microwave assisted extraction, enzyme assisted extraction, pulsed electric field assisted extraction for the extraction of bioactives from fruit and vegetable by-products is limited and requires to be explored further. The development of equipment avoiding direct contact of components such as ultrasonic horns with the fruit and vegetables during extraction would enhance the commercial visualization of the UAE of bioactive compounds which is limited till now.

## 9. Conclusion

The changed outlook of fruit and vegetable processor from discarding the by-products considering it of negligible value to utilizing them for their sustainable development has brought non thermal extraction techniques such as ultrasound assisted extraction in limelight. The emphasis on waste utilization, component recovery, environment protection, green technology has added impetus on UAE. UAE has shown to be better equipped to extract the bioactive compounds from fruit and vegetable by-products without damaging the structure of volatile bioactive compounds. In the current review effect of each factor affecting the extraction of bioactive compound from fruit and vegetable by-products has been highlighted and the optimized extraction variables summarized. There are many more unutilized by-products where these concepts can be utilized and recovery of valuable bioactive components can be made. The demand for the natural bioactive compound is increasing and UAE of the bioactive compounds from fruit and vegetable by-products can meet this demand through continuous improvement in technology and focussed research.

## CRediT authorship contribution statement

**Kshitiz Kumar:** Conceptualization, Methodology, Writing - original draft. **Shivmurti Srivastav:** Visualization, Writing - review & editing. **Vijay Singh Sharanagat:** Validation, Supervision, Project

administration, Writing - review & editing.

## Declaration of Competing Interest

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

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## Appendix A. Supplementary data

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