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Microwave-assisted extraction of bioactives in fruits and vegetables: a comprehensive review

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Abstract

Fruits and vegetables are integral parts of the daily diet and consist of inedible peel, pomace, and kernel, which are rich in bioactive compounds (BACs). These BACs can be extracted by microwave-assisted extraction using microwave energy. Microwaves are non-ionising electromagnetic radiations with a frequency range of 300 MHz to 300 GHz. Its instrumentation includes a magnetron, waveguide, applicator, and circulator. Microwave extractors are of two types: open and closed. The former is used to extract thermoinsensitive compounds, and the latter to extract thermolabile compounds. Microwave extractors work with dual mechanisms called dipolar rotation and ionic conduction. They help to rupture the cell wall and release BACs into the solvent. The factors *viz*., solvent type and concentration, microwave power, extraction time, solvent-to-sample ratio, extraction temperature, and sample properties affect the extraction efficiency. Microwave-assisted extraction provides benefits such as higher yields, low extraction time, low solvent consumption, and compatibility with other methods.

Keywords: Fruit and vegetable waste; Bioactive compounds; Microwave-assisted extraction; Ionic conduction and dipolar rotation.

1. Introduction

Fruits and vegetables are enriched with nutritious compounds such as vitamins, minerals, fibres, phenolics and carotenoids, making them an integral part of the human diet. For consumption, some portions like peel, rind, core, seed, pomace, and kernel are removed, considered inedible, and waste. However, they are rich in bioactive compounds (BACs) like pectin, dietary fibres, tannins, phenols, carotenoids, and anthocyanins (Table 1). They are potential sources of antioxidant, antimicrobial, and anticancerous properties (Daduang et al., 2011).

Banana peel, which is 30% of the total fruit weight, is rich in dietary fibres and phenolic compounds (Gonzalez-Montelongo et al., 2010). Mangosteen fruit rind, which accounts for two-thirds of its weight, is rich in anthocyanins (Netravati et al., 2024). Pineapple waste comprises of 70% of total fruit weight, which includes peel, core, trimmings, and crown, which are rich in bromelain, proteins, and peptides (Mala et al., 2021). Apple pomace 30% of raw material) is rich in polyphenols, triterpenes, fibres, and vitamins (Cristina-Gabriela et al., 2012). Watermelon rind accounts for one-third of total fruit mass and can be used as raw material for pectin preparation (Petkowicz et al., 2017). Avocado seeds constitute 13–17% of the fresh fruit and contain tannins, phenolic acids, and flavonoids (Araujo et al., 2020). These BACs from food waste can be extracted and incorporated into diets to overcome undernourishment, affecting around 735 million people globally (von Grebmer et al., 2023).

On the other hand, food waste disposal in the environment causes adverse effects to it. The incineration of food waste releases acid gases and furans, and landfills release methane, which is a significant greenhouse gas (Khan, 2021). In the above context, there is a dire need and sound scope for valorising food waste. Extraction is one sustainable way for the valorisation of food waste.

The extraction of BACs can be done by using different conventional methods. However, they have drawbacks like more time

Table 1. Bioactive compounds in food waste

Sl. No.	Food waste	Bioactive compounds	Reference
1	Tomato waste	Pectin	Lasunon and Sengkhamparn (2022)
2	Blueberry bagasse	Anthocyanins	Ferreira et al. (2020)
3	Black tea waste	Caffeine and catechin	Serdar et al. (2017)
4	Onion peel	Phenols and flavonoids	Das and Mandal (2015)
5	Mango peel	Phenols	Dorta et al. (2013)
6	Grape seed	Phenols	Krishnaswamy et al. (2013)
7	Annatto seed	Polyphenols and carotenoids	Quintero Quiroz et al. (2019)
8	Grapevine residue	Polyphenols	Jesus et al. (2019)
9	Eggplant peel	Phenols and anthocyanins	Doulabi et al. (2020)
10	Hibiscus calyx	Anthocyanins	Cassol et al. (2019)
11	Date seed	Phenolic compounds, dietary fibre, and vitamins	Ranasinghe et al. (2024)
12	Black carrot pomace	Polyphenols	Kumar et al. (2019)
13	Chaya leaves	Phenols	Rodrigues et al. (2020)
14	Fig leaves	Polyphenols and furanocoumarins	Yu et al. (2020)
15	Jackfruit peel	Pectin	Govindaraj et al. (2018)
16	Mango peel	Pectin, polyphenols	Rojas et al. (2015)
17	Pistachio shell	Phenolic compounds	Maccarronello et al. (2024)
18	Pomegranate peel	Phenolic compounds	Kaderides et al. (2019)
19	Saffron tepal	Flavanols, anthocyanins	Cerda-Bernad et al. (2022)
20	Melon peel	Pectic polysaccharide	Golbargi et al. (2021)

consumption (Carbone et al., 2020), higher solvent requirement, low efficiency, and hydrolytic degradation of some compounds (Sarfarazi et al., 2020). In this regard, we need an economical and eco-friendly technology that can give higher yields in a short time without degradation of BACs. One such technology is microwave-assisted extraction (MAE).

2. Microwaves

These are non-ionising radiations that contain two oscillating perpendicular fields, *viz*., electric field and magnetic field. They lie between the frequency range of 300 MHz to 300 GHz (Airouyuwa et al., 2023), with a wavelength range of 1 mm to 1 m (Kaatze, 1995; Letellier and Budzinski, 1999; Pinto et al., 2021). The energy of a microwave photon is 0.037 kcal/mol (Gaba and Dhingra, 2011), which is very low compared to the energy required to break a molecular bond, and speed is way faster than the time required by a molecule to relax.

3. Applications of microwaves

Microwaves can be used for diverse purposes like sterilisation (Potato, onion, carrot, and red pepper were sterilised at 100 °C for three min. to control *Bacillus amyloliquefaciens*, Cho and Chung, 2020), pasteurisation (Apple juice of Cv. Golden delicious was pasteurised at 80–90 °C (600–720 W) for 25 s, Mendes-Oliveira et al., 2020), drying (spinach leaves were dried at 750 W for 290 to 430 s, Ozkan et al., 2007), thawing (strawberry and mulberry frozen fruits thawed at 184 W, four °C preserved the antioxidant capacity, Le et al., 2018), blanching (Broccoli Cv. Empress blanched at 700 W for four min. retained its properties in long term storage, Brewer et al., 1995), and extraction (Optimum quality phenolic compounds were extracted from grape pomace at 1,000 W, 10 min (Da Rocha and Norena, 2020). This review emphasises the extraction of BACs using microwaves.

4. Microwave-assisted extraction

The polar solvents that are in contact with the sample are heated by using microwave energy to extract the BACs present in the sample (Sharma and Dash, 2021).

Microwave energy is delivered through polar solvents to generate heat by converting electromagnetic radiation into thermal energy. Dielectric constants and dissipation factors are crucial for transforming electromagnetic radiation into thermal energy (Pimentel-Moral et al., 2018). Microwave-assisted extraction includes three sequential phases: desorption, internal diffusion, and external diffusion. In the first phase, the BACs present in the sample matrix are separated from the active sites of the sample. The second phase involves the diffusion of solvent into the sample matrix, and the last phase consists of the release of solutes from the sample matrix into the solvent (Thaiphanit et al., 2020).

4.1. *Microwave extractors*

Microwave extractors majorly include four major components:

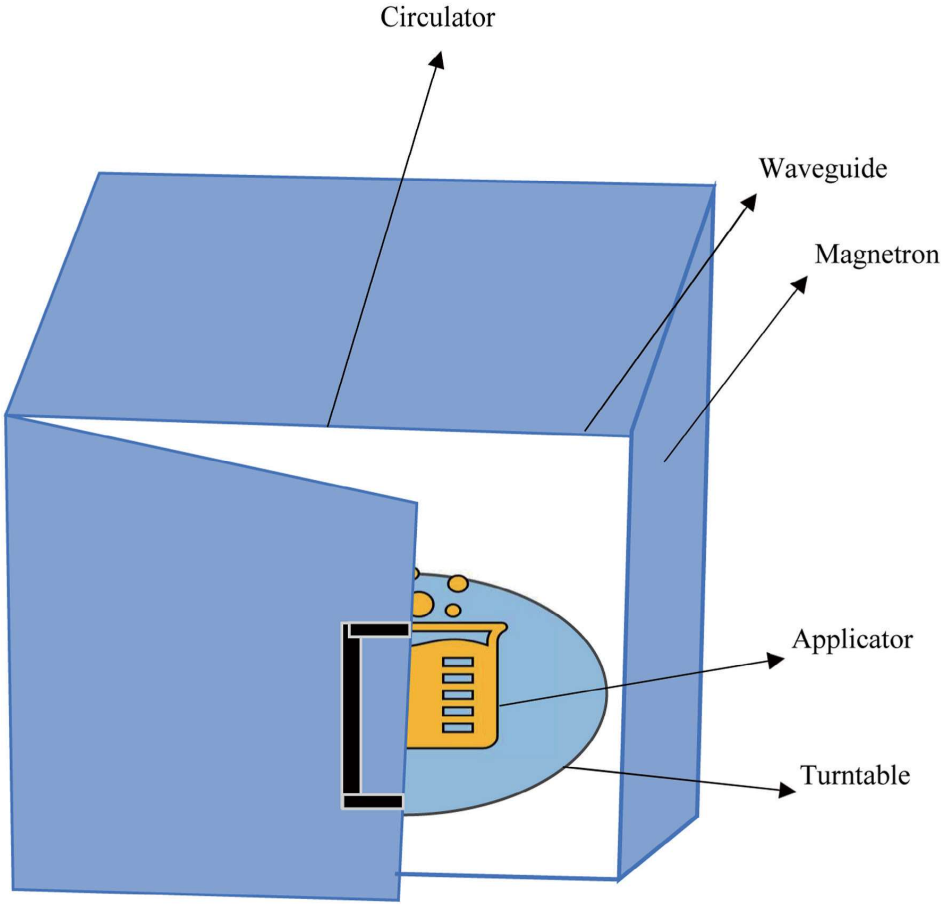

Figure 1. Microwave instrumentation.

a magnetron (microwave generator), waveguide (propagates the microwaves into the microwave cavity), applicator (extraction vessel), and circulator (allows microwaves to pass forward movement only) (Figure 1) (De Castro and Priego-Capote, 2011). These are of two types, viz., closed type and open type extractors (De Castro and Castillo-Peinado, 2016; Li et al., 2004)

Closed vessel extractors (Figure 2) are usually multimode type, and the microwave treatment is done at high pressure (Pressurised extraction) with a random dispersion of microwaves inside the cavity. The turntable helps bring an even distribution of microwaves inside the cavity regardless of the position of the sample. Due to the elevated pressure levels inside the vessel, higher temperatures can be easily achieved. There is no significant loss of volatiles in this. Extraction can be done simultaneously for multiple samples. The disadvantage of this method is that it cannot be used to extract thermolabile compounds (Delazar et al., 2012).

In open vessel extractors (Figure 3), the microwave treatment is done at atmospheric pressure and given only to a specified region (Focused extraction) where the sample is immersed in the solvent that absorbs microwaves (Li et al., 2004). The upper region of the flask remains calm as the glass is transparent to microwaves. Further cooling is brought by using a water condenser. This is safer to use for the extraction of thermolabile compounds as it is operated at atmospheric pressure and low temperature. The disadvantage of this method is that multiple samples can not be operated simultaneously (Delazar et al., 2012).

4.2. Principle and mechanism of MAE

During MAE, microwaves pass through solvent and plant particles. The latter contains vacuoles with a certain moisture content (Chan et al., 2016). Moisture heating occurs due to dual mechanisms called ionic conduction and dipolar rotation (Gomez et al., 2020). Ionic conduction (Figure 4) refers to the electrophoretic migration of ions in accordance with the changing electric field, which generates friction between ions and the medium, resulting in the liberation of heat. Dipole rotation (Figure 5) arises when the permanent dipole tries to align its phase in line with the changing electromagnetic field (Veggi et al., 2012). The continuous randomised forced movement results in heating (Mendes et al., 2016). These mechanisms result in the vaporisation of moisture and a tremendous increase in internal pressure inside the cell matrix, which leads to rupture of the cell wall and allows active leach out of phytoconstituents into the solvent (Figure 6) (Dhobi et al., 2009).

5. Factors affecting MAE

Solvent type and concentration, microwave power, extraction time, solvent-to-feed ratio, extraction temperature, and sample properties affect the efficiency of MAE (Figure 7) (Xie et al., 2014; Bachtler and Bart, 2021; Daliri Sosefi et al., 2024; Elakremi et al., 2022).

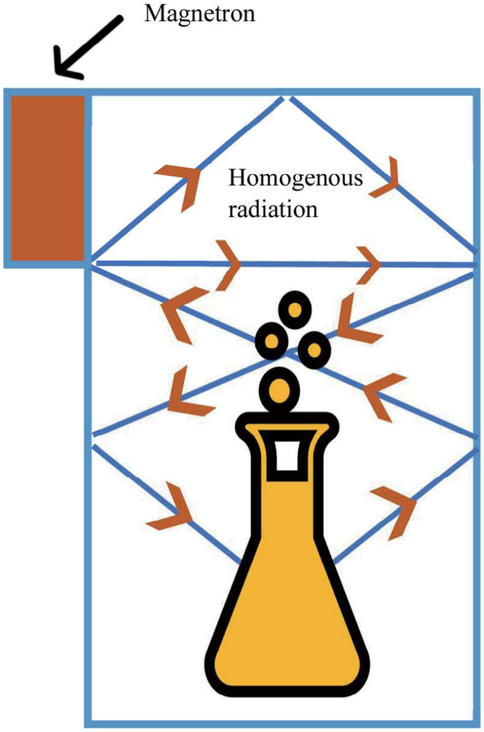

Figure 2. Closed type extraction.

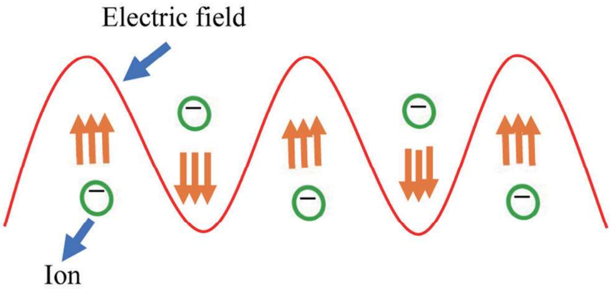

Figure 4. Ionic conduction.

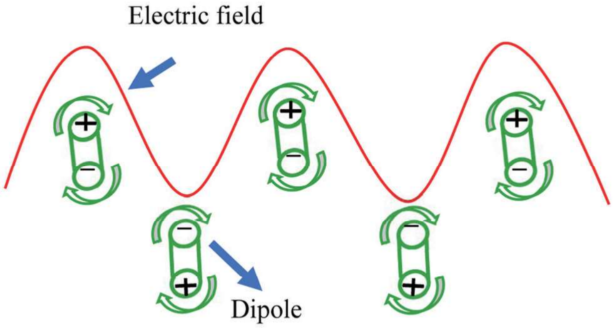

Figure 5. Dipolar rotation.

5.1. Solvent nature and volume

The Dielectric constant, solvent penetration and its interaction with the sample matrix, molecular size, and solubility of the compound of interest are considered for improving extraction efficiency. A high dielectric constant of the solvent will enhance the extraction process more rapidly (Ihsanpuro et al., 2022). The solvent volume must be sufficient to immerse the sample throughout the extraction process (Veggi et al., 2012). Solvents with lower molecular size and higher polarity will enhance extraction yields by improving

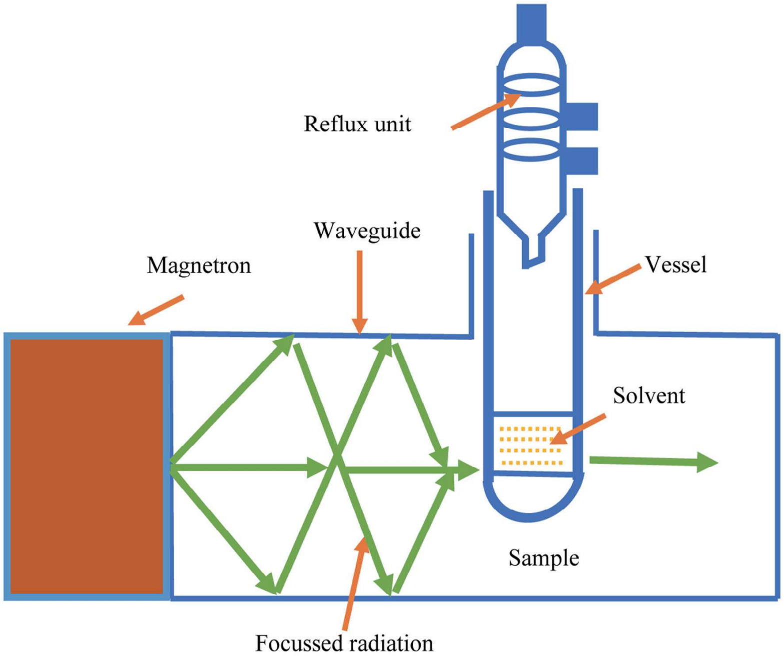

Figure 3. Open type extraction.

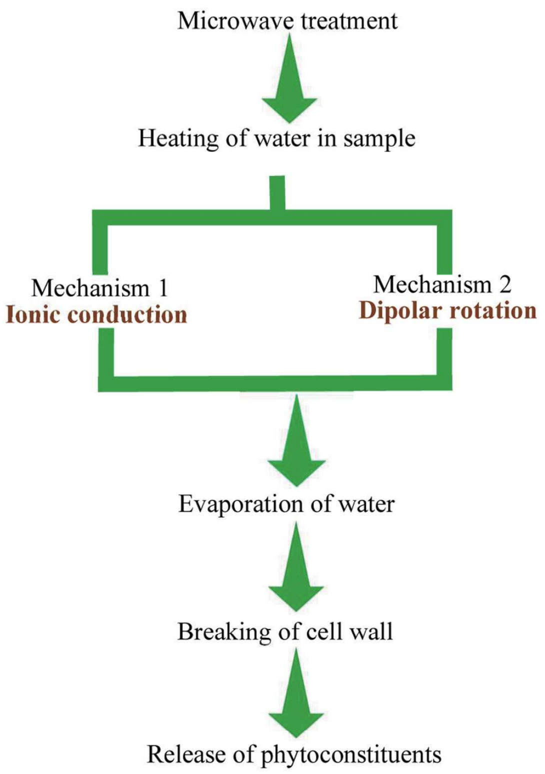

Figure 6. Flow chart of microwave assisted extraction.

heating and making it easy to penetrate into the solvent. Methanol gives a higher extraction yield, having a lower molecular size and higher polarity, but ethanol is the widely used solvent because of safety concerns (Chan et al., 2017). Karami et al. (2015) investigated the effect of solvents (ethanol 80%, methanol 80% or water) on the yield of phenolic compounds from liquorice roots. From the study, they inferred that the higher extract was obtained by ethanol; it also improved the extract's total phenolic content and antioxidant activity.

5.2. Microwave power

Microwave power influences the quantity of extracted compounds and extraction time. Elevated power levels provide a higher yield. It causes localised heating in the sample, which helps destroy the plant matrix so that the BACs can be diffused into the solvent. The increase in power level will increase the extraction yield in a shorter time. Conversely, a high-power level decreases the extraction yield by degrading the thermolabile compounds (Veggi et al., 2012). Luo et al. (2021) conducted a study on antioxidant activity and total phenolic content of *Akebia trifoliate peel* extracts at different power levels from 300–800 W. From the study, they inferred that the total phenolic content and antioxidant showed a positive trend from 300–500 W, above this power levels they are decreased significantly. Doulabi et al. (2020) conducted a study to evaluate MAE's effect on eggplant peel by-products' bioactive compounds. They reported that extraction yield was increased with an increase in microwave power from 100–300 W. Bioactive active alkaloids were extracted from lotus plumules using microwave-assisted extraction (Xiong et al., 2016). They reported that an increase in the liquid-to-solid ratio from 5:1 to 20:1 increased the extraction yield, and thereafter, there was no rise in yield.

5.3. Extraction time

Extraction time usually correlates with microwave power and shows an inverse relationship. At each power level, an optimum

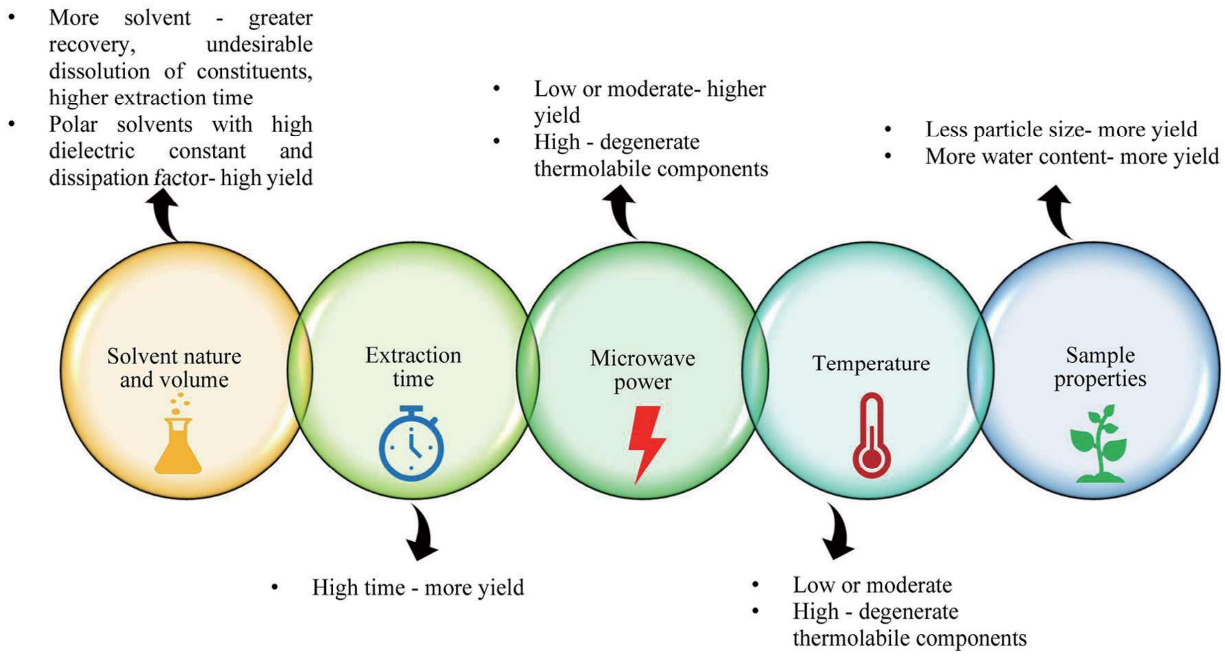

Figure 7. Factors affecting MAE.

extraction time will give a better extraction yield (Chan et al., 2017). Dielectric properties of the solvent also influence it. The solvents with higher dielectric constant heat up highly under overexposure, thus risking the yield of thermolabile (Veggi et al., 2012). A study was conducted to determine the effect of extraction time on antioxidant activity and total phenolic content of Akebia trifoliate peel extract and inferred that an increase in time enhances the yield until optimum conditions; later on, it decreased (Luo et al., 2021). A study by Alara et al. (2021) reported that the phenolic content increased with an increase in time from two to four minutes, and after that, there was a rapid decline in the phenolic content in *C. papaya* leaf.

5.4. Extraction temperature

Temperature is a crucial factor in extraction. Increasing the extraction temperature will lead to higher diffusion, improving the release of BACs into the solvent. It also decreases the solvent's viscosity, resulting in easy penetration into the cells and enhancing solute desorption into the solvent. Higher temperature leads to the loss of thermolabile compounds (Vladić et al., 2020), increased extract impurities, and poor stability of the final extracted compound (Bachtler and Bart, 2021). Zheng et al. (2011) extracted polysaccharides from pumpkins and studied the effect of extraction parameters on extraction yield. From the study, they reported that a temperature of 70 °C is suitable for breaking analytic matrix bonds and gives a higher yield of polysaccharides. At a temperature of more than 70 °C, the yield of polysaccharides declined and gave scorched extract.

5.5. Sample properties

Extraction of BACs from an intact plant part is complex and inefficient. The sample's particle size characterises the amount of disruption and influences the extraction yield. Smaller particle sizes give higher extraction yields, as the diffusivity of the BACs increases with smaller particles due to the larger contact surface area (Chan et al., 2017). Particles of large and tiny sizes will reduce the extraction yield because of smaller surface area and easy agglomeration, respectively (Xiong et al., 2016). Smaller particle size gave a higher yield of seed oil (32%) in pomegranate compared to the larger particles (11%) under the same extraction conditions, *i.e.*, 238 W, 6:1 solvent to sample ratio, and 5 minutes extraction time (Keskin Cavdar et al., 2017). some BACs extracted through MAE are listed in Table 2.

6. Benefits of MAE

Microwave-assisted extraction has the advantages such as low extraction time (Garrido et al., 2019; Bener et al., 2022) and solvent consumption (Chumnanpaisont et al., 2014; González-de-Peredo et al., 2022), higher extraction yields (Thaiphanit et al., 2020), low cost (Dahmoune et al., 2015; Mellinas et al., 2020), better potential for automation (Weremfo et al., 2020), low energy consumption (Sarfarazi et al., 2020), high quality extracts (Olalere et al., 2021; Vélez-Erazo et al., 2021), and compatibility with other methods.

Despite these benefits, it is adopted only in laboratories due to the difficulty in scale-up and optimisation of the process parameters for extraction of BACs from different samples (Chan et al., 2016).

7. Conclusion

Microwave-assisted extraction is a sustainable technology for extracting bioactive compounds from fruit and vegetable waste. The extraction process involves the open type and closed type extractors. Ionic conduction and dipolar rotation are the two critical mechanisms involved in the extraction process. The extraction parameters are specific to each BAC based on the matrix properties. This technology gives more extraction yields quickly, with less solvent and energy consumption. Microwave-assisted extraction plays a crucial role in the extraction of thermolabile compounds due to the lower exposure times to heat. Further research has to be done to determine the combined abilities of this technology with other methods to achieve synergistic effects from both technologies. Optimisation of extraction parameters, i.e., microwave power, extraction time, temperature, and solvent-to-feed ratio is required to avail the maximum BACs from the sample.

Acknowledgments

Not applicable.

Ethics statement

Not applicable.

Conflict of interest

The authors declare that there is no conflict of interest among them.

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Table 2. Bioactive compounds extracted through MAE

Sl. No.	Food waste	Bioactive compound extracted	Parameters used	Results	Reference
1.	Sweet lemon peel	Pectin	Microwave power (300 W, 500 W, and 700 W), time (1 min, 2 min, and 3 min), pH (1.5, 2.25, and 3.0)	700 W, 3 min at pH 1.5 gave maximum pectin yield	Rahmani et al. (2020)
2	Saffron tepals	Anthocyanins	Solvent ratio (32.5–77.5 ml/g), extraction temperature (35–75 °C), and time (7.5–12.5 min)	The solvent ratio of 77.5 ml/g, extraction temperature (48 °C), and 9.3 min gave the highest amount of anthocyanins	Jafari et al. (2019)
3.	Olive leaves and flowers	Phenolic compounds	Microwave power (800 W), aqueous ethanol (0–100%), solid to solvent ratio (5–15 mg/ml), temperature (60–110 °C), citric acid concentration (1–5 M)	80% aqueous ethanol, 97.5 °C, 7.5 mg/ml, and 2 M gave maximized yield of antioxidant compounds	Darvishzadeh and Orsat (2022)
4.	Pomegranate waste	Phenols	Microwave power (150–750 W), solvent: solid ratio (10–30 mL/g), extraction time (2–10 min), and ethanol concentration (20–100%)	Ethanol concentration (50%), solvent/ solid ratio (25:1 mL/g), extraction time (4 min), and power (450 W) gave higher extraction yield	Mali and Kumar (2023)
5.	Potato peel	Phenols, ascorbic acid	Microwave power (800 W), methanol (30, 65, and 100%), and solvent to feed (40 mL/2 g)	67.33% aqueous methanol, 15 minutes extraction time gave optimum results	Singh et al. (2011)
6.	Pistachio hull	Phenolic compounds	Microwave power (80–140 W), extraction time (1–5 min), solvent to sample ratio (8:1 to 20:1), and ethanol concentration (30–70%)	140 W, 3 min, 1:14, and 50% strength gave the highest phenolic content	Ozbek et al. (2020)
7.	Legume by-products	Inositol	Temperature (50–120 °C), time (3–30 min), and ethanol strength (0–100%)	50 °C, 30 min and 100% ethanol being the optimal conditions for both pods and seeds	Zuluaga et al. (2020)
8.	Chestnut shells	Phenols	Microwave power (200–1,000 W), time (3–15 min), and solvent concentration (0, 0.05, 0.10, 0.15, 0.2 mol/L) NaOH	800 W, 12 min., and 0.115 mol/L NaOH concentration gave the highest phenolic content	Kocer et al. (2024)
9.	Cashew apple bagasse	Phenols, ascorbic acid, and tannins	Microwave power (280 W, 430 W, and 530 W), time (30 s, 75 s, 120 s), and bagasse to solvent ratio (1:15, 1:22.5, and 1:30)	560 W microwave power, 110 s treatment time, and 1:30 (w/v) bagasse to solvent ratio gave the highest yields with good antioxidant activity	Patra et al. (2021)
10.	Asparagus roots	Phenols, flavonoids, and saponins	Extraction time (15 s, 35 s, 55 s, 75 s, and 95 s), concentration of methanol or ethanol (10%, 30%, 50%, 70% and 90%), microwave power (100 W, 250 W, 400 W, 550 W, and 700 W), solid/liquid (S/L) ratio (1:4, 1:28, 1:52, 1:76 and 1:100 g/mL)	Extraction time 57 s, 63% of ethanol, extraction power 460 W, and S/L ratio 1:68	Zhang et al. (2019)

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