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Microwave-Based Technological Approaches for Sustainable Management of Fruit and Vegetable Residues

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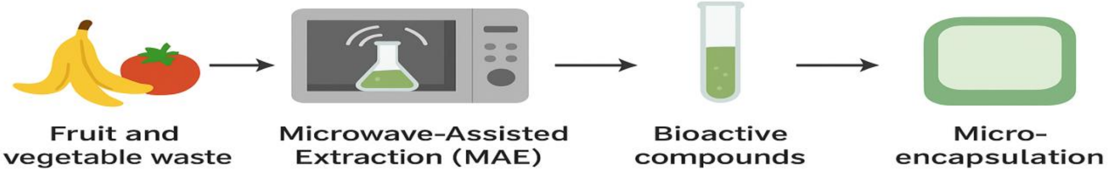
Abstract

This review paper analyses the recovery and safe use of bioactive compounds in waste products of fruits and vegetables with specific reference to the application of microwave-assisted extraction (MAE) and microencapsulation. The peer-reviewed literature was analysed to understand the extraction efficiency, solvent effects, stabilisation strategies and safety issues of the waste-derived bioactive ingredients. The literature review shows that MAE is effective and fast at extracting polyphenol and other bioactive compounds compared to traditional methods. Nevertheless, some of the studies indicate that there are any possible safety concerns such as the leaching of pesticide residues, heavy metals and other pollutants in the final extracts in case of raw waste material and absence of adequate screening and control of the processes. Microencapsulation has been largely reported as an efficient strategy to improve the stability, shelf life and controlled release of bioactive compounds however the selection of the encapsulating materials and processing conditions is a critical aspect in the product safety. Altogether, the results indicate that MAE and microencapsulation can be an effective approach to valorising food waste into functional components, but quality control, approved processing technologies, and food safety legislation are the key to safe food usage.

Graphical Abstract



Highlights

- Bioactive compounds are found in the fruits and vegetable waste.
- Microwaves are used to extract, and it reduces time used in the processing.
- The uncertainties involved in safety are the pesticide residues, and heavy metals among others.
- Microencapsulation assists in enhancing bioactive compounds functional and stability.
- There is a need to have quality controls and regulatory compliance in food applications.

Key words
Microencapsulation; food waste valorisation; microwave-assisted extraction (MAE); ultrasound-assisted extraction (UAE); bioactive substances; the circular economy and functional foods

I. Introduction

Agricultural by-products and food waste have become highly scientifically interesting as the potential sources of biologically active compounds. Worthwhile phytochemicals in many fruits, vegetables, and processing residues include carotenoids, flavonoids, anthocyanins, lycopene and other phenolic compounds which demonstrate antioxidant, antimicrobial, anti-inflammatory and chemoprotective actions (Sorrenti, Buro et al. 2023). Historically, much of these resources were discarded or abandoned and this resulted to further environmental pollution and economic wastage (Demirbas 2011).

Nevertheless, this increasing trend of natural health-promoting ingredients, along with the worldwide move towards sustainability, has prompted researchers and industries to consider waste streams as alternative, renewable sources of functional biomolecules (Singh and Negi 2025). This trend has been enhanced by recent developments in the science of extraction. New methods such as ultrasound-assisted extraction and microwave-assisted extraction, supercritical fluid extraction, and co-extraction can be used to achieve higher yields, less solvent consumption, lesser processing duration, and enhanced maintenance of compounds that are sensitive to heat (Akalan et al., 2025).

The techniques do not only make the recovery more efficient but also increase the stability and bioavailability of the extracted substances, which can be incorporated into food, pharmaceutical, and packaging (Putnik, Lorenzo et al. 2018). The adoption of nanotechnology has also allowed controlled delivery and enhanced functional performance of bioactive made out of waste matrices. Although these advantages exist, there are still a number of limitations to the widespread use of them (Jayabal and Prabhakar 2025). The safety of the product, the management of contaminants, the adherence to the regulations, the uniformity of the quality of the product during the processing are the issues that should be taken into consideration before commercialisation. Changes in the composition of raw materials and the requirement to have cost-effective and scalable processing further affect industrial adoption (Tawo and Mbamalu 2025). On the whole, food waste valorisation is a sustainable approach that should be consistent with the principles of the circular-economy and minimize the environmental impact of the problem and help to create new value-added products (Dhiman, Thakur et al. 2025). This method can provide a great potential to the future developments in food science, biotechnology, and nutraceutical development by converting waste products into useful commodities with high health and technological values (Singh and Negi 2025).

Microwave technology

Microwaves are electromagnetic waves, which are wavelengths between 1 mm and 1 m and frequencies between 300 MHz and 300 GHz (Ray 2024). This is the property of the microwaves that allows it to penetrate materials and consequently gives maximum internal heating (Joardder and Karim 2025). This is why microwaves can be used in extraction and processing applications on a large scale. The microwave based systems operating on Maxwell equations control distribution of electromagnetic energy, the geometry of cavity and material interface are also taken into account (Cai, Wu et al. 2024). Transformation of the microwave energy to thermal energy and it is a function of dielectric properties of the material i.e. the permittivity and the loss factor. Such features will be likely to determine the effectiveness of the energy absorption to transform it into heat and, therefore, directly affect the efficiency of the extraction applications that rely on the use of microwaves (Horikoshi, Catala-Civera et al. 2024). It is a controlled heat process, which is used in efficient extraction of bioactive compounds in natural materials under a microwave-assisted extraction (Zhang, Li et al. 2025). The heating of MAE is realized mainly due to the effect of the rotation of dipoles and ionic conduction (Sun, Wang et al. 2016), (Bhadange, Carpenter et al. 2024).This results in the better extraction process that reduces the time needed to process, at the cost of the minimal amount of solvent used. Therefore, MAE is a widely used technique of producing high-value bioactive compounds like alkaloids, terpenes, quinones, and polyphenols in an environmentally friendly way (Bhadange, Carpenter et al. 2024). This renders MAE to be a superior option over other conventional extraction methods since high yields are achieved as well as less energy and eco-friendliness is used (Shrivastav, Prava Jyoti et al. 2025).

Biomolecules extraction from waste food

MAE can be considered one of the most important and sustainable methods of attaining Granular Activator Carbon (GAC) (Shi, Xu et al. 2024). MAE has rapidly become one of the most preferable methods of the efficient and sustainable isolation compounds of biological activity of solid matrices. Figure 2. Graphical illustration of the extraction of bioactive substances in fruit and vegetable waste using microwaves. It reduced the number of minutes spent in the conventional extraction methods to several (Bhadange, Carpenter et al. 2024).

Among the major problems associated with environmental perspective is food waste management, in which in India, with the fast urbanization process, population growth as well as the process of industrialization, the number of wastes generated is growing fast. Food wastes cannot be discarded in a way that it does not influence the environmental factors, and this may pose the potential health risks to the individuals unless it is discarded in a proper manner (Wani, Rather et al. 2024). The beverage sector is the largest generator of food waste accounting to 26 percent, followed by dairy and ice cream sector (21.3) and fruit and vegetable processing and preservation (14.8) (Ali, Raza et al. 2022). The majority of food processing techniques (grinding, drying, pasteurization, extrusion, extraction, and mixing) cause the massive loss of possible bioactive substances (Li, Liu et al. 2024). The concentrated sources of these materials include some of the proteins, alkaloids, carotenoids, phenolics, vitamins, dietary fibers, and polyphenols and food products produced during food processing like jam, jellies, and marmalades.

Following the extraction of juice or other value addition, the fruit and vegetable processing industry, specifically juice, results in enormous quantities of pomace, or a mixture of pulp, peel, seeds, and stems (de Menezes, Sousa et al. 2025; Socas-Rodriguez, Alvarez-Rivera et al. 2021). Such phytochemicals may then be incorporated to other food products like improving their nutritional, chemical and physical properties (Lopes, Madureira et al. 2025). Traditionally, pomace may be used in the form of cattle feed, fertilizer, compost matter, and a minor ingredient of drinks. However, the more recent research tells us that it may be utilized as the source of natural nutrients and as the functional additive in order to make sure that the foods with bioactive compounds may be used to supplement and replace synthetic ones (Perez-Grijalva, Herrera-Sotero et al. 2018). More to the point, the veggie wastes too are one of the most vital sources of phytonutrients that are very critical in the formation of good health and prevention of most diseases. These wastes are in pre-harvest phase and in harvesting phase such as leaves, twigs and post-harvest stems that are abandoned in the field after harvesting. Being the product of vegetables, these by-products are therefore a highly rich source of health-promoting compounds that are underestimated and underutilized (Ben-Othman, Joudu et al.,2020).Microwave-assisted extraction is a popular method to retrieve numerous bioactive compounds in plant-based wastes and the best extraction parameters are summarised in Table 1 (Zhao et al., 2018; Gonzalez-de-Peredo et al., 2022; Zheng et al., 2013; Vo et al., 2024; Rajabi et al., 2025; Karunanithi et al., 2025).

Polysaccharides

The extraction of plant- and fruit-based products exhibited through microwave-assisted extraction (MAE) has emerged as one of the most promising techniques of efficient recovery and preservation of bioactive compounds in the past several years. Hu, Zhao et al. (2019) demonstrated that it is possible to remove polysaccharides in the fruits of *Camptotheca acuminata* with help of MAE and then the physicochemical properties and the bioactivity could be assessed. Their ends showed that the processing in the presence of microwaves had a significant enhancement of extraction efficiency and has not compromised the structural integrity and functional attributes of the extracted biomolecules (Zou et al., 2024). Liquid food systems have also been addressed with the microwave-based techniques in order to increase bioactivity retention and safety of a solid food matrix, besides liquid food. Perez-Grijalva, Herrera-Sotero et al. (2018) maintained the microbial stability of the juice by the then microwave treatment of the blackberry mash followed by ultrasound processing of the juice, which did not change functional quality of the juice during the storage. An ideal combination of the enhancement of the major quality determinants, including total polyphenols content, anthocyanin stability, colour density, polymeric pigmentation, and antioxidant activity was achieved by the authors with the assistance of response surface methodology in order to achieve a balanced improvement in nutritional value and safety (Leyva-Jiménez et al., 2022.In the same way, the efficiency of microwave-assisted and hybrid microwave protocols to optimise the cosponsor ship of bioactive compounds beneficial to plant products have been confirmed in several studies (Arasi, Rao et al. 2016; Rolim, Seabra et al. 2020; Golbargi, Gharibzahedi et al. 2021). Combined, these data reveal the versatility, stability and process efficiency of microwave-based solutions to increase the extraction rate, reduce the time of action, and preserve the activity of natural bioactives (Bagade & Patil ,2021).

Pectin

The U.S. food and drug administration (FDA) acknowledge pectin as a safe food ingredient under the GRAS (Generally Recognized As safe), list (Espitia, Du et al. 2014). In a study by Mierczynska, Cybulska et al. (2017), the pectin-enriched fractions obtained after the extraction using citric acid varied in relation to their rheological and chemical qualities depending on the source. In a work on the extraction of pectin in dragon fruit peel and passion fruit peel, the authors compared the traditional heating method to the microwave-assisted extraction (MAE). (Putra, Rizkiyah et al. 2024). These results indicate that the proposed technology is effective because previous researchers have shown that microwave-assisted technology can enhance pectin recovery in fruit waste (Karbuz and Tugrul 2021; Van Tai, Minh et al. 2023).

In a different study, (Spinei and Oroian 2022) were able to extract pectin, using MAE. experiments were conducted at varying pH levels on the use of different levels of microwave intensity and extraction time. Optimal time was recorded at 700 W after 180 seconds and pH 1.5 after which it was purified by using ethanol and dried. Fresh and dry grape pomace was found to have good extraction efficiency. Kamal, Ali et al. (2020) optimized the extraction of pectin using *Dillenia indica* using MAE and the Box-Behnken design. They determined that the ratio of solid to liquid, pH, and microwave power were some of the influential factors. Optimally (495.48 W, pH 1.99, 8.93 minutes, 1:20.59), they obtained a yield of more than 20 and there was a strong correlation between these parameters and pectin yield.

Some researchers have demonstrated better extraction of pectin with MAE as compared to the traditional extraction (CE) and ultrasound-assisted extraction (UAE). The pectin yield was higher in the Golden Delicious *apple pomace* at low pH, prolonged extraction period, and high liquid-solid ratio (LSR). MAE has been yielding 1.18-19.88% and UAE yielded 0.98-9.91% (Gurev, Cesko et al. 2023). Similarly, citric acid-assisted extraction of the apple pomace produced better yields with CE (23.26) and MAE (23.32) than UAE (9.18) at the same LSR (Dranca, Vargas et al. 2020).On the whole, various researchers have demonstrated that the use of microwave-assisted extraction (MAE) is the best method when it comes to the extraction of pectin in diverse sources of fruits (Karbuz&Tugrul, 2021). MAE has advantages such as decreased energy consumption, time reduction and increased relative to the conventional methods. It is the most popular in the use of modern pectin extraction because of its effectiveness and environmental friendliness (Haque et al., 2025). The new developments in extraction technology in the recent past have sought to enhance both the yield and efficiency without compromising on environmental sustainability (Pell et al., 2021).

Essential oils

Essential oils are a product of aromatic plants and may be considered as secondary metabolites. The oils are possible to receive following the extraction of various plant organs roots, stems, leaves, flowers, fruits, and other tissues (Figueiredo et al., 2008).Their aromatic, phenolic and terpene compounds are rich and make them have a distinguishable smell, and a high amount of antioxidant property (Pinto et al., 2021). The enzyme-preventing ability and antibacterial, antifungal, anti-inflammatory, anti-viral, and anti-cancer activities of essential oils are the main reasons why they are popular in the pharmaceutical, cosmetic, and food sectors (Peng, Zhao et al. 2022). Microwave hydro diffusion and gravity (MHD) method of extracting essential oils initiates when the water reaches the boiling point that causes the first drop of oil to be released (Chouhan et al., 2019). The process of oil separation is extensive since the heat is maintained at this temperature level. Water evaporation in the plant cells is fast to raise the internal pressure and consequently, the cell walls rupture as a mode of facilitating the shooting out of the vital oils (Simon, 1974).

The concentration difference between the inside and the outside of the plant cells also promotes diffusion of mass and the effectiveness of the extraction process becomes greater (Peng, Liu et al. 2022).

The optimal ability to extract *Cinnamomum camphora* fruit peel oil using the solvent-free microwave extraction (SFME) was 80.35 +- 1.88 mg/g of pure oil. Optimization of Box-Behnken (BBD) response surface methodology (RSM) was such an approach. Compared to hydro distillation (HD), SFME gave superior outcomes in yield, extraction time and sustainability to the environment. The analysis of the extraction was done with the aid of gas chromatography-mass spectrometry (GC-MS) and scanning electron microscopy (SEM), which confirmed that SFME is a perspective and non-toxic procedure of extracting essential oils (Liu, Li et al. 2022). Generally, the microwave-based processes including MHD and SFME are the processes of extracting essential oils that are fast and solvent-free, in comparison with the conventional distillation method, which is energy-consuming (Alvi et al., 2022).

Cold plasma atmospheric microwave treatment for essential oils extraction

Cold plasma is a novel non-thermal method which is based on active charged particles and ionized gases to disinfect the deleterious microorganisms. It is the fourth state of matter which is scientifically defined as a situation when the gas molecules are high-energy and are ionized (Deepak, 2022).The food industries have become interested in this technology because it has the potential to enable longer shelf-life, reduce microbial contamination as well as enhance protein functionality (Zhao et al., 2023).More importantly, the cold plasma is used in the treatment of wastewater, biofilm management, modification of packaging, enzyme inactivation, toxin degradation, and minimization of thermal damage (Heydari, Carbone et al. 2023).

In a recent study, 50 g of powdered betel leaf was put in an atmospheric pressure cold plasma system provided with ZeonicsSystech at 35 kV and allowed to operate with a 30 mm electrode gap in 10 min. The plasma treatment was followed by the use of UWave 1000 oven (630-810 W, 60-120 s) where the samples were subjected to microwaving and then hydro distillation method was used with 1 L of water in a 2 L flask. The extracted oil was partitioned, dried and kept at 4ºC. The optimum conditions of CPAMW at 738 W, 98 s, and 104 min, respectively, gave the highest essential oil recovery yield (3.33 +- 1.2%), and the total phenolic content (59.97 +- 1.7 mg GAE/mL) (Karunanithi, Guha et al. 2023). In another research, (Shokoohi, Ebadi et al. 2024) examined the effects of atmospheric plasma pretreatment and other variables like air and argon (Ar) gas which affected cumin seed essential oil yield and quality. When ACP was pretreated by scanning electron microscopy, the seed surface was identified to have microstructural cracks that enhanced the process of extracting oil. The seeds treated with Ar recorded the highest browning index and change of colour; the oil yield also increased up to 44 per cent. relative to the untreated seeds. In addition, the Ar treatment increased the cumin aldehyde content of 47.9 percent to 56.4 percent showing that the value of the oil improved.

Microwave assisted hydro-distillation for extraction of essential oils

MAHD has been proved as an effective method of separating vital oils out of moist citrus peel wastes without the use of chemical solvents, minimal power consumption, and a yield of oil of 1.8% that is equivalent to the standard hydro-distillation (Bustamante et al., 2016).The eco-friendliness and high efficiency of MAHD indicates its promise to recover large volumes of essential oils of citrus wastes at large scale to green biorefinery applications (Bustamante, van Stempvoort et al. 2016). On the same note, ILMAE has proven highly effective in the extraction of key oils as well as lignans of Schisandra chinensis. This technique was faster with 0.25 M 1-lauryl-3-methylimi dazolium bromide and less harmful to the environment than the standard method (Li, Li et al. 2019).

Polyphenols

Polyphenols are the large plant secondary metabolites and are widely recognized as having wide bioactivities. Polyphenols are the large plant secondary metabolites and are widely recognized as having wide bioactivities. Even though they are structurally diverse, they are critical in plant defense and have a far-reaching effect on the nutritional and sensory properties of the plant-derived foods, which are immensely in demand in the food and pharmaceutical sectors (Leonard et al., 2022).In recent times, there has been increased interest in the utilization of microwave extraction as an efficient, quick and environmentally harmless method of extracting polyphenols in plant materials (Ameer et al., 2017). As an instance, MAE of Camellia oleifera fruit hulls in optimum conditions (15.33:1 mL/g, 35 minutes, 76 °C) produced 15.05% polyphenols, of which gallic acid was the primary product. In a similar manner, MAE of mulberry fruits (Morus alba L.) at 210 W power, 8 minutes, and 40% ethanol allowed extracting and accurately identifying various polyphenols in mulberry fruits with the use of the HPLC technique (Zhang et al., 2011).Response surface methodology has also increased the efficiency of MAE, as in Melastomasanguineum that brought about 39.02 mg GAE/g DW and outcryed the standard methodologies such as maceration and Soxhlet extraction in terms of time, temperature, and solvent use (Zhao et al., 2018).MAE has also been optimized on Pistacia lentiscus leaves and fruits where the manipulated temperature, microwave power and extraction time allowed high recovery of polyphenols which were later profiled by

UPLC/ESI-MS² and significant levels of antioxidant activity (Elez Garofulić et al., 2020).Also, vacuum microwave-assisted aqueous extraction (VMAAE) has become a sustainable variant of MAE, which enhances the yield of phenolic compounds of pomegranate peels in a statistically optimized mode (Skenderidis et al., 2020).Kinetic experiments with beetroot seeds also confirm the benefits of MAE as grounded seeds have a higher phenolic content (19.1 mg GAE/g DW) and the extraction requires less energy, leading to highly efficient yields than untreated samples and other ultrasound-based extraction methods (Stoica et al., 2025).All these studies point to MAE as a very promising method of maximizing the yield of polyphenols in a wide variety of plant-origin products and minimizing the time of the extraction, consumption of solvents, and energy (Shi et al., 2005).

Anthocyanins

The anthocyanin pigments are the leading pigments which produce the characteristic colours of most fruits and are predominantly located in the skin of grape with only a few cultivars which retain them in the pomace (Delić et al., 2024). Their extraction is also optimally extracted through microwave-assisted extraction (MAE), a method that is highly praised to provide a rapid heating procedure and low solvent consumption (Nonglait et al., 2024).A fractional factorial design conducted on grapes demonstrated that solvent composition exerted the greatest influence on extraction, and the most successful outcomes were achieved when using 40% methanol-water at 100 ºC over 5 minutes which resulted in very stable and reproducible extracts (Liazid, Guerrero et al. 2011). The same has been reported in the case of blueberry powder, with ethanol concentration, temperature, extraction time, and solid-to-liquid ratio being the main factors, the maximum extraction rate of 73.73% was achieved at 47 ºC, 55.5% ethanol, 1:34 rate, and 7 minutes (Zheng, Xu et al. 2013).

MAE is also effective in the extraction of anthocyanin in red raspberries. Response surface methodology was used to determine the optimum conditions with 366 W, a 4:1 solvent to material ratio, giving 12 minutes extraction yielding 98.33 percent of total red pigments (Sun, Liao et al. 2007). When using acidic solvents, extraction in black currant residues improved significantly with the use of MAE. Optimization of MAE (pH 2, 700 W, and 10 minutes) reduced the extraction time of 300 minutes down to a mere 10 minutes and cut the solvent consumption by half and yielded 20% more anthocyanins than traditional mechanisms in mulberry fruits (Zou, Wang et al. 2012). Bran of black rice was also extracted efficiently using a 50:50 blend of 0.1 M ethanol and citric acid (81.44 percent recovery), as well as a 50:50 blend of 0.1 M ethanol and ethanol acids (81.38 percent recovery) (Leonarski, Kuasnei et al. 2025). A better method (iMAE) was developed to recover anthocyanin in purple sweet potato pomace, and in 320 W and 500 seconds in 1:3 ratio and 30-percent ethanol, prevented the starch degradation and produced 31.16 mg/100 g (Liu, Yang et al. 2019).In red cabbage, the response surface modelling revealed that microwave power, solid-to-solvent ratio, and 9.95 minutes in 30-per cent eth Another more developed approach was a combination of MAE with enzyme-assisted extraction of Purple-heart Radish, in which an optimized enzyme input and microwave conditions were used to obtain a high yield of anthocyanin 6.125 mg/g (Chen, Zhong et al. 2023). On the whole, these investigations show that MAE and its hybrid solution types are effective fast, efficient, and sustainable to recover anthocyanin in various plants.

Flavonoids

Flavonoids are vital bioactive compounds known for their strong antioxidant, anti-inflammatory, cardioprotective, and anticancer properties. While plant-based foods are their major dietary sources, significant losses often occur during processing, making efficient extraction methods essential for preserving their functional benefits (Routray and Orsat 2012). Recent advancements highlight microwave-assisted extraction (MAE) and hybrid techniques as powerful tools for maximizing flavonoid recovery from plant materials. A combined microwave–ultrasound extraction method was optimized for red onion skins, where response surface methodology identified key factors influencing extraction. Optimal conditions 30 mL/g solvent–solid ratio, 60 seconds of microwave exposure, 15 minutes of sonication at 70 °C, and 70% ethanol yielded 19.15 mg/g of quercetin and 39.67 mg/g total flavonoids (Velisdeh, Najafpour Darzi et al. 2024). Similarly, flavonoid extraction from passion fruit peels was cleaned with mixture of ethanol, acetone, and water, with augmented simplex–centroid and Box–Behnken designs determining the ideal solvent ratios and extraction parameters to achieve up to 17.74 mg GAE/g db (Vo, Phan et al. 2024). MAE proved notably more effective than classical extraction for *Terminalia chebula*, where operating at 100 °C with a 40 mL/g solvent-to-feed ratio increased the equilibrium flavonoid yield by 14.17% and nearly doubled the effective diffusion coefficient, highlighting the enhanced mass-transfer efficiency under microwave heating (Krishnan and Rajan 2016). In lemon myrtle leaves, response surface methodology identified optimal MAE conditions that produced a high flavonoid yield of 384.57 ± 2.74 mg CE/g DW, confirming MAE as a green and highly efficient extraction strategy (Saifullah, McCullum et al. 2021). Optimization studies using Box–Behnken design also improved flavanol extraction from onions, where methanol concentration, pH, temperature, and sample-to-solvent ratio were key variables. The best extraction was achieved with 93.8% methanol, pH 2, a temperature of 50 °C, and a ratio of 0.2:17.9 g/mL, producing 7.557 mg/g of flavonols(González-de-Peredo, Vázquez-Espinosa et al. 2022). A synergistic ultrasonic–microwave extraction process applied to sweet potato leaves achieved 91.65% efficiency under optimized conditions (57 °C, 76 seconds, 1:40 solid–liquid ratio, and 72% ethanol), and HPLC analysis identified eleven flavonoids with strong antioxidant activity (Liu, Mu et al. 2019). MAE was also optimized for fenugreek seeds using a one-factor-at-a-time approach. The highest flavonoid yield was obtained using 60% ethanol, a 1:10 feed-to-solvent ratio, 70 °C, 600 W power, and 3 minutes of extraction (Liu, Mu et al. 2019). In aubergine skin, microwave extraction using 50% aqueous ethanol produced extracts rich in flavonoids with strong lipid peroxidation inhibitory and superoxide-scavenging abilities (Salerno, Modica et al. 2014). Orange pomace also showed promise as a flavonoid source when vacuum microwave-assisted extraction was optimized through a predictive cubic RSM model, confirming that power level, water ratio, and extraction duration significantly influenced yield (Petrotos, Giavasis et al. 2021). Finally, ginger flavonoids were effectively extracted using MAE optimized at 640 W, 80% ethanol, a 1:30 material ratio, and 25 seconds of irradiation, producing a flavonoid yield of 16.97 mg/g (Liu, Hu et al. 2010). Collectively, these studies demonstrate that microwave-based and microwave-assisted hybrid extraction techniques offer faster, greener, and more efficient flavonoid recovery than conventional methods, making them highly suitable for food, pharmaceutical, and nutraceutical applications.

Carotenoids

Carotenoids are important natural pigments present almost in every fruit and vegetable that are beneficial to human health reducing the likelihood of chronic diseases like cancer, cataracts and macular degeneration (Bhatt et al., 2020). Thus, the food and pharmaceutical industries have shown them much attention. One of such sources with great antioxidant potential is the Gac fruit peel that is otherwise considered a waste (Kha et al., 2013).Experiments with ethyl acetate and microwave-assisted extraction (MAE) indicated that the effectiveness of the extraction process was related to the power of the microwaves and time and the highest productivity was achieved at 120 W after 25 minutes (Destandau& Michel, 2022).Intermittent MAE was also reported to increase the β-carotene and total carotenoid content over continuous MAE, but retain high antioxidant potential (Dharmendrasinh, 2021).Likewise, clementines yield one more by-product, which is peels, which were discovered to have a high amount of carotenoids (Kadi et al., 2022).Optimization of MAE with 68% hexane, 561 W power, 7.64 minutes of irradiation and solvent to solid ratio of 43 mL/g gave a yield of 186.55 mg/g carotenoid production, which was better than maceration and Soxhlet extraction. The waste in the processing of carrot juice has also been successfully used in carotenoid recovery by MAE in which flaxseed oil was used as a green solvent (Nonglait& Gokhale, 2024).Additional indicators of the efficiency of MAE are studies of Seabuckthorn pomace, in which solvents that are environmentally friendly like corn and olive oil yielded carotenoid contents of between 26.91 and 34.35 mg/100 g, respectively (Sharma et al., 2022).HPLC profiling revealed that the olive oil extracts had the greatest amount of β-carotene and lycopene (Seppanen et al., 2003).Besides that, MAE has also been streamlined to extract carotenoids in peach palm in which pretreatment conditions comprised of pressure cooking, drying, grinding, and storage at 20 °C temperature (Srivastav &Karunanithi, 2024).The optimal carotenoid extraction (61.57 mg/g) at optimum energy of 300 W in three minutes with six extraction cycles was observed to yield the highest carotenoid extraction which validated the combination of these two factors as offering the most efficient extraction conditions(Georgiopoulou et al., 2023).

Lycopene

The antioxidant potential of bioactive compounds like lycopene has been appreciated due to its effects in offering protective action of the body to diseases that are caused by oxidative stress (Imran et al., 2020).Most of the red-coloured fruits commonly contain these natural pigments and they have both nutritional and remedial value that is increasing their popularity in the current food and health industry (Leong et al., 2018).They are also being incorporated in most of the foodstuffs as natural colorants, antioxidant additives and even functional ingredients in order to augment nutritional values (Faustino et al., 2019).The most recent researches are thus aimed at determining the more effective means of extracting lycopene of apricot, tomato, papaya, pink guava, and sea buckthorn berries wastes since their traditional modes of extraction have several constraints (Chaudhary, Khalid et al. 2024). Since the compound is nonpolar and heat-sensitive, the compound is extremely hard to extract by the traditional methods, thus, MAE of tomato peels has been optimized to extract lycopene (Fatima, 2025).Response surface methodology has also optimized in a systematic way several important operational factors such as the solvent composition, the power of the microwave and total energy input (Ismail et al., 2013).The maximum yield value obtained was 13.592 mg/100 g of all-trans lycopene with the 0:10 solvent system and at 400 W (Ho et al., 2015).The following was also discovered: ethyl acetate was more suitable in extracting lycopene in waste tomato peel compared to hexane (Ho, Ferruzzi et al. 2015). The article also revealed that tomato peel by-products were also a promising source of lycopene and MAE was a quick and efficient solution of extraction. The distribution of lycopene isomers was verified by HPLC-DAD that justifies the application of MAE in the context of high-quality recovery of lycopene also in the present work (Ho, Ferruzzi et al. 2015). Residues from processing of Carica papaya L. have also been extracted using ultrasound-assisted extraction (UAE) as an effective method for lycopene recovery. Single-factor experiments combined with response surface methodology produced a reliable predictive model with $R^2 = 0.9147$ and $p = 0.001$, confirming the efficiency of the optimized extraction conditions (Li et al., 2015).

UAE caused better lycopene yield compared to the traditional and Soxhlet methods, and crude extract could be used as food natural ingredient (Li, Li et al. 2015). All in all, these publications bear witness to the fact that such new extraction techniques as MAE and UAE are ensuring high lycopene yields, better bioactivity, and increased extraction compared to the traditional methods, hence they are gaining more popularity as a technology in the food, nutraceutical, and pharmaceutical sectors. (Gil-Chávez et al., 2013)

Role of antioxidants in food industry

The high level of applicability of antioxidants is attributed to low cost, common practicality and high performance in the food industry to stop food spoilage (Lourenço et al., 2019).They extend the shelf life of food products mainly by inhibiting oxidative reactions, and not by improving colour or flavour (Gray et al., 1996).TBHQ- Tertiary Butylhydroquinone, BHA- Butylated Hydroxyanisole, BHT- Butylated Hydroxytoluene and PG- Propyl Gallate are artificial antioxidants that have been a long time addition to food (Esazadeh et al., 2024).However, the industry is gradually moving towards the use of natural sources of antioxidants, as the demand of natural and clean-label products by the consumers grows (Balasubramaniam et al., 2023).Natural and added antioxidants delay the oxidation of lipids leading to the rancidity and unwanted flavours (Pegg & Shahidi, 2012).The ultimate safety of synthetic additives has caused fear, and the result has been the need by scientists to find safer alternatives that are based on plants. Ascorbic acid, a-tocopherol and rosemary extract are natural antioxidants that are used in food systems in the modern industry (Manuelian et al., 2021).The identification of strong antioxidants compounds in by-products and waste products of food and their applicability in the product usage is one of the latest fields of study. Lipid oxidation is also known to reduce sensory quality as well as produce toxic compounds (Hadidi et al., 2022).This means that antioxidants are very important in maintaining nutritional and safety of foods throughout storage and transportation (Valenzuela et al., 2003).New tools of analysis are being developed in which measurements and predictions of the level of oxidation are more accurate so that the industries could choose the effective strategies of antioxidants (Apak, 2019).The natural antioxidants found in plants and other biological sources are under review as safe, sustainable and environmental (Lourenço et al., 2019).They form a major component of the modern food preservation due to their capability of maintaining the quality of food (Amit et al., 2017).

Preservatives

The primary cause of food spoilage is the growth of microbes that are likely to occur without any symptoms and finally cause detectable and sensory alterations to render food unsafe (Rawat, 2015).Microorganisms thrive under favorable environment including nutrients, moisture, pH, oxygen and redox balance (Srivastava et al., 2023).The spoliation happens when the microbial metabolites are exposed to an area whereby they impact the quality and even the health hazard (Alum et al., 2016).Food industry depends on a very high number of preservation methods to avoid this degradation. There are certain chemical preservatives that were used previously to prevent multiplication of microbes (Gould, 2000).One of the oldest and well used preservatives of various foods is the sodium chloride. Inhibitors like the organic acids including acetic, benzoic, propanoic as well as sorbic, are also effective in acidic foods as well as in processed meat products containing nitrates and nitrites which are used in the inhibition of Clostridium botulinum maturation (Silva & Lidon, 2016).Similarly, the sulphur dioxide and sulphites are typical in such beverages as wine and juice and dried fruit (Freedman, 1980).Nisin and natamycin are also two natural antibiotics that are used to a certain degree, in preserving some foods to avoid bacterial and fungal contamination (Delves-Broughton, 2008).The EU Directive 89/107/EEC legal provisions allow essential additives and not toxic additives in addition to being misleading to the consumers (Oreopoulou et al., 2009).This has been observed in the recent years despite the frenzied shift in Europe towards natural preservatives that guarantee quality of products, the absence of the E-number labelling of products (Galanakis, 2022).This is particularly on the low processed foods that are being retailed to the health-conscious consumers. The natural preservation agent has been the focus of the scientific study on the agro-food byproducts, fruit peels and fruit seeds due to this change (Maddaloni et al., 2025).They usually have antimicrobial bioactive compounds in their extracts. Indicatively, the high concentration of phenolics in the turmeric extracts, and oils means that they are highly antibacterial and antifungal (Tonin et al., 2021).Such byproducts may be used as natural substitutes to the artificial preservatives with the relevant safety authorization in the industrial food processing (Novais et al., 2022).Another source that can be used is winery residues. Proanthocyanidins (highly bioactive and astringent) are compounds that are extracted prior to fermentation like stems and grape clusters (Teixeira et al., 2014).Besides they are not utilised in the wine making production, their formulation is useful in the food preservation and health related products (García-Lomillo & González-SanJosé, 2017).The modern research could investigate the antimicrobial packaging as well as its application in addition to the chemical and natural preservatives as other alternative way of microbial spoilage control (Fadiji et al., 2023).An example is when making the sheets of paper on the basis of mixed-fibre formulations that are reinforced with sodium carboxymethyl cellulose (Huang, 2025).These materials are very potent antibacterials when impregnated with the food grade lactoferrin or the food grade lysozyme (Barbiroli et al., 2012).The practice of using sheets composed of lysozyme was the best because it reduced the growth of microorganisms on beef slices that were utilizing the treated packets (Nattress et al., 2001).

Microencapsulation of Functional Ingredients in the Food and Agricultural Fields

Most of the bioactive ingredients used in the preparation of functional foods such as vitamins, antioxidants, plant-based compounds, probiotics, and omega-3 oils are easily destroyed by heat, light or acidity, exposing them to such conditions (Mondal et al., 2021).Over these conditions they may deteriorate their structure and diminish their effectiveness (Sanchez-Silva et al., 2011).To counter this obstacle and make sure that bioactives will not lose their properties until they arrive at their target location in the body, several microencapsulation technologies have been produced (Ye, Georges et al. 2018). Microencapsulation refers to the process of encircling active substances with a protective wall material to avoid degradation, increase stability and have the ability to release them in a controlled manner (Jyothi et al., 2012).Some of the common techniques used include double emulsions, nanoencapsulation, hybrid wall systems, and crosslinking methods (Mohammadalinejhad& Kurek, 2021).The action of these microcapsules is also determined by factors like size, morphology, encapsulation efficiency, structural stability and release behaviour, all of which directly affect the availability in vivo of the released encapsulated compounds (Yun et al., 2021).Since the shell material used dictates the release process of the bioactives within the body, microencapsulation has become fundamental in enhancing the use of bioactives and food value in ingredients (Onwulata, 2013).Led by the growing consumer demand in the foods that aid general well being, studies in the last 10 years have gone on a frenzy in developing new processes and materials, which help food products in increasing their functionality. Functional foods are increasingly being enriched with various bioactive compounds, but their integration can cause various problems, including chemical instability, food components interactions, or sensory alterations (Vlaicu et al., 2023).The application of microencapsulation especially in industry has been shown to overcome such challenges through the formation of a physical barrier around the actives, protection of degradation of the actives, and controlled or targeted release of actives, thereby preserving its biological activity (Sanguansri and Ann Augustin 2010).Microencapsulation has been shown to be effective in industrial applications in the protection of bioactives, flavour delivery in foods, delivery of probiotics, and incorporation of sensitive functional blending ingredients within structured food formulations as a way to maintain the biological activity of the act Nonetheless, the food industry has a low profit margin than pharmaceutical industry and thus there is urgent necessity of low cost and scalable and efficient technologies to encapsulate. The last nature of microcapsule be in the form of reservoir or matrix system is determined by the physicochemical characteristics of the active core material, the encapsulating agent selected and the encapsulation method applied (Kuang, Oliveira et al. 2010). Even though the encapsulation systems have been a subject of a lot of research, very few have been translated into full scale industrial processes. The most recent ones are the use of microencapsulated pomegranate extract (Punica granatum L.) in ice cream and wild blackberry (*Rubus ulmifolius*) extract in algae microparticles in the yoghurt. These researches show how microencapsulation could be practically used in improving the functional value, stability, and sensory attributes of commercial food items (Ribeiro, Ruphuy et al. 2015). Figure 1. The flow of the scheme of waste-derived materials to extracting compounds and encapsulation in microscales to enhance stability and usage. This is normally done using the encapsulation methods mentioned above that will guarantee control delivery and better protection of sensitive bioactive (de Vos et al., 2010).

Microencapsulation Techniques

Spray-drying

Among the most widespread forms of heat-sensitive bioactive substances connected with evaporation of solvents within a short period of time and exposure time, which in turn lessen thermal degradation, is spray drying (Kandasamy and Naveen 2022). It is highly effective in the extraction of moisture and further stores the active components into a safeguarding solid skeleton, therefore, is most suggestively deployed in the distribution of the functional ingredients in food systems (I Re 1998) (Amiri, Nezamdoost-Sani et al. 2024). However, conditions of processing strongly affect the performance of the technique. As an example, extremely high ratios of gas and liquid in gas-admixing foam spray drying such as gas-liquid ratios (GLR 6.43×10^{-3} kg/kg) and inlet temperature (215 °C) reduced the encapsulation efficiency by more than 50% through structural rupture and leakage of oil (Lewandowski et al., 2019).In its turn, moderate drying temperatures and controlled GLR allowed to create particles with an enhanced flowability and density and achieved an encapsulation of up to 80% (Lewandowski, Zbicinski et al. 2020). Spray drying microencapsulation of volatile compounds with gum arabic and maltodextrin have also been promising as their walls of microencapsulating citral and linalyl acetate (80:20 w/w) though very high inlet temperature (300–400 °C) did not bring about future degradation of the chemical because of very short residence time during the drying (Nguyen et al., 2021).It could also utilize maltodextrin instead of gum arabic up to 60 percent concentration and volatile fraction could also be up to 84 percent (Bhandari, Dumoulin et al. 1992). Similarly, the thermal and oxidative stability of squid oils were also enhanced when they were encapsulated using gelatin, caseins and maltodextrin. The incorporation of lecithin and Avicel augmented stability whereas elimination of a-tocopherol reduced protection which indicated the complementary effect of natural antioxidants (LIN, LIN et al. 1995). Another potential replacement to the traditional spray drying is the encapsulation with the Lipid solids. Spray chilling or Spray cooling technique is also referred to as spray congealing technique that was first introduced to be utilized in pharmaceutical industry, but is now widely application in food systems (Thakur, Kaushal et al. 2025). Lipid droplets that are active and contain cocoa butter, beeswax, or palm oil are melted and added to a chilled vessel to produce solid lipid microparticles in this technique (Noor, Azmi et al. 2025). Such technological advantages of this technique include increased physical stability, reduced hygroscopicity, desirable taste and odour, controlled solubility, and increased protection to bioactive compounds, which are fragile (Okuro, de Matos Junior et al. 2013). The other complementary approach is spray freezing that makes microspheres of a matrix type in which enclosure of the bioactive material is homogenously suspended in the particle. Dense and tightly-packed microspheres of homogenous physical characteristics can be achieved with proper selection of carrier materials and as such can be used in the stabilization of frail ingredients (Favaro-Trindade, Okuro et al. 2015). The establishment of vitamin B12 (cyanocobalamin) in solid lipid microparticles (SLMS) is also another evidence of the superiority of lipid-based microencapsulation because vitamins are fragile molecules that tend to be inactive in the natural diet (Favas, Almeida et al. 2024). The spray cooling method was used to obtain six forms of SLM lecithin and vitamin B12 at varying concentrations. This value was found in its yielding microparticles: 13.28–26.99 mm average diameter of the particles, high yields (80.7–99.7 percent) of production, and high encapsulation rates (76.7–101.1 percent) (Collazos Paucar et al., 2016).It was observed that encapsulation was very useful in stabilizing the vitamin B12 in such a way that after 120 days, 91.1 percent of the vitamin was still present as compared to 75.2 percent that was the case with the rest of the non-encapsulated vitamin (Parin, 2021).Controlled release behaviour based on the Lecithin also demonstrated that spray cooling is cheap, solvent-free, and efficient method of preserving labile micronutrients (Mazzocato, Thomazini et al. 2019).

Air suspension coating

Air-suspension method is an established micro encapsulation method that is commonly used in food industry as well as drug delivery system (Werner et al., 2007).It is done by fluidizing solid particles in an upward blast of air and then removing a coating made of a wall material dissolved in a volatile solvent. When the solvent is rapidly evaporated, a cohesive protective film is created around the core material and this forms a stable microcapsule (Turton & Cheng, 2005).The process usually achieves relatively big particle sizes as compared to other methods of encapsulation (Farzi and Gheysipour 2023). Another useful use of this method was the application of an air-suspension fluidized-bed system coupled with a Wurster coater to obtain core shell microcapsules loaded with Lactobacillus paracasei. During the initial coating process, a preparation containing trehalose, maltodextrin and probiotic cells was sprayed onto weight free crystalline cellulose forming free-flowing dry particles which were highly viable in cell count (10^9 cfu/g) (Semyonov et al., 2012).The paper also investigated the effect of the process operating variables including inlet air temperature, spray flow rate, concentration of particles and cells, and encapsulation matrix composition on probiotic survival (Semyonov, Ramon et al. 2012).

Extrusion

This review nullifies the practicality of probiotics in gastrointestinal disorders of grave severity and obstacles that are associated with them. In an attempt to improve those survival and effectiveness, the microencapsulation processes particularly the more advanced one, co-extrusion have been broadly researched into (Bhutada et al., 2025). The use of the technique is considered to be dependable due to the fact that it ensures microbeads that safeguard the probiotic cells against an adverse environment (Thantsha, 2008). The other processing parameters are also realized within the study that can lead to larger sizes of the microbeads and low cell viability. In addition, the co-extrusion is compared to the outdated extrusion technologies to demonstrate the difference in the efficiency of encapsulation and stability (Rabanel et al., 2009). The attribute of encapsulated and non-encapsulated probiotics is also examined in connection with the review in respect of their resistance to gastrointestinal digestion and storage conditions. In summary, the results demonstrate that microencapsulation is relevant to the protection of probiotics (Barajas-Álvarez et al., 2023)activities and their overall therapeutic potential (Lai, How et al. 2022).

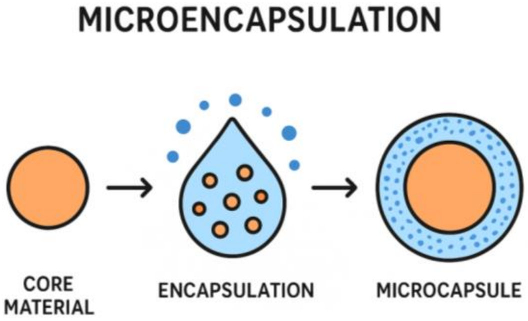


Fig 1 Schematic Representation of microencapsulation of bioactive materials

Table 1: Recovery of TPC and flavonoids from various source with parameters

Bioactive compounds(source)	**Extraction Time (min)**	**Ethanol proportion (%)**	**Microwave power (W)**	**Liquid. Solid ratio (mL/g)**	**Recovery of TPC (mgGAE/g)**	**Recovery of Total Flavonoids (mgQE/g)**	**Recovery of condensed Tannins (mg/g)**
Polyphenols (Mulberry fruits) (Zhao, Zhang et al. 2018)	8	40	210	-	**15.05**	-	-
Flavonoids(Red onion skin)(González-de-Peredo, Vázquez-Espinosa et al. 2022)	1(MW) + 15 (US)	70	-	30	-	**39.67**	**19.15**
Flavonoids (Passion fruit peel)(Vo, Phan et al. 2024)	Variable	Ethanol yes , Acetone, Water	-	-	17.74	8.11	-
Anthocyanins (Red raspberries)	12	Acidified solvent	366	4	-	-	-
Anthocyanins(Blueberry powder)(Zheng, Xu et al. 2013)	7	55.5	-	34	-	-	-
Pectin (Kiwi peel) (F Rajabi et al.2025)	3	Acidic (HCL)	360	-	-	-	-
Essential oils (Betal leaf; Cold plasma +MW)((Karunanithi, Guha et al. 2023)	~2	-	630-810	-	Total phenolics **59.97** mg GAE/mL	-	-

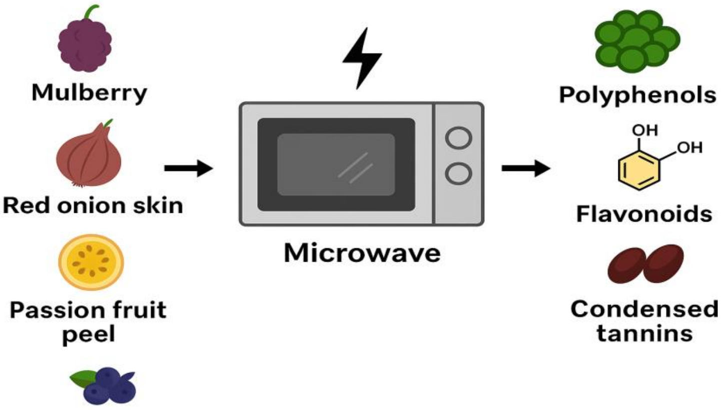


Fig 2 Schematic representation of microwave processing of food waste products for bioactive compounds

Rules and regulations

In this segment, the core opportunities and regulatory challenges concerning the valorisation of food waste are summarized and there is a high need to formulate more efficient and balanced regulatory frameworks (Almansour and Akrami 2024). The global standards such as the ISO 14001 provide a structured guide in the implementation of the sustainable waste-management and resource-efficiency systems in the industries (Devkota, Montet et al. 2017). The raw materials acquired out of the food-waste in the European Union undergo strict regulatory control and legislation that governs the activity to ensure the safety of the population and enhance the openness of the market. The terms of product use in terms of food by-products which can be used as an ingredient or an additive can be found in terms of product use in Appendix Codex Alimentarius and EC Regulation No. 178/ 2002 (Kravchenko 2024). The materials that cannot be classified in the categories are taken on board under the Novel Food Regulation (EU) 2015/2283 that requires a safety dossier to be comprehensive. The EFSA asks the professional examination of botanical preparations, including the chemical constituent, mode of extraction and part of the plant utilized (EFSA Panel on Nutrition, Allergens et al. 2024). Such tests must include toxicity and toxicokinetic tests which are the OECD/ EU tests that will guarantee that there are no toxic contaminants. Thus, labeling of nutraceuticals with agro-industrial residues by those in question should be backed by important scientific data until then market approval is granted (Vilas-Boas, Pintado et al. 2021).

The U.S. regulates dietary supplements as a subset of the Dietary Supplement Health and Education Act of 1994 (DSHEA), where the producers take the preliminary responsibility of regulating drugs and labeling correctly thereafter, followed by post regulation of the products by its commercials and FDA (Vilas-Boas, Pintado et al. 2021). The functional food producing companies in Japan are regulated by the Consumer Affairs Agency where they are categorized under various headings (Foods for Specified Health Uses and Foods with Nutrient Function Claims). They should have shown safety, quality, and healthy physiological advantages (Watanabe 2024). Food safety and functional food in India including botanicals, nutraceuticals, probiotics and novel foods are controlled by the FSSAI, but there are no obvious controls on the use of agro-food waste. All these regulatory frameworks point out to the opportunities and the challenge of transforming food waste into global market ready and value-added products.

Recent innovations

The latest developments in valorisation of food waste are more oriented at transforming waste-derived bioactive compounds into effective and sustainable applications (Bekavac et al., 2025). Figure 3. Graphical illustration of new processing processes to transform food waste into value added products. Some of the EU countries have tightened their food waste disposal policies to reduce wastage, forcing food industry to consider high-value food recovery options (Watanabe 2024). As an example, France imposes fines on retailers that dispose of edible food, and Korea encourages joint efforts between NGOs, government bodies, and the business sector in reducing the amount of waste by 20 percent (Watanabe 2024). In the United States, the consumers are urged to avoid overordering and excessive consumption by means of awareness campaigns (Martin-Rios, Hofmann et al. 2020). Among the new fields of innovation, the creation of edible and biodegradable packaging with the addition of bioactive compounds of waste food can be highlighted. These are environmentally friendly material and increase food quality and safety. Nanotechnology advances these systems by adding nutrients, antioxidants, antimicrobials, and other functional compounds that are carried via nanofibers, nano emulsions, and encapsulated carriers (Kamble, Singh et al. 2025) to them. Active packaging pushes protective factors or absorbs harmful factors and successfully increases the shelf life of food products (Trajkovska Petkoska, Daniloski et al. 2021). All these innovations point to the fact that the food waste rich in bioactive material can be redesigned into new, sustainable solutions that can enrich quality improvement, minimize waste, and contribute to the contemporary circular-economy practices.

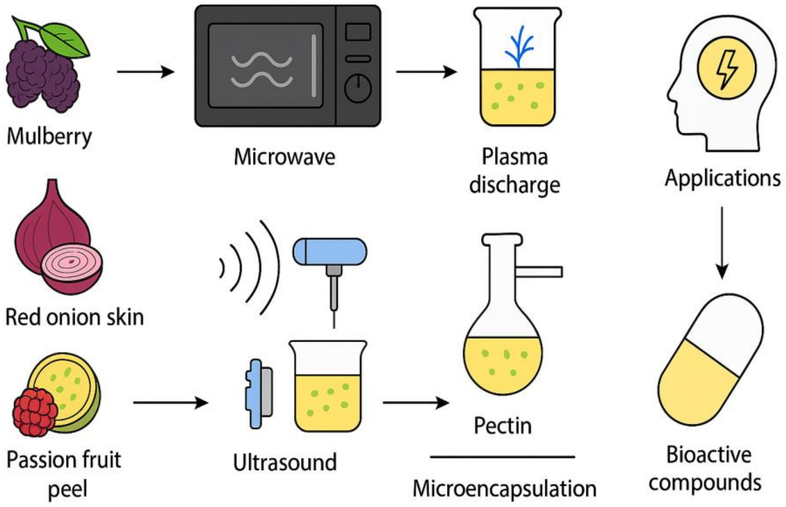


Fig 3 Innovative techniques for valorising food waste into bioactive compounds

Safety and health concerns in reuse waste food for development of new product

Ensuring the safety of bioactive-based food products derived from waste materials is a critical challenge, as these ingredients may carry chemical, microbiological, or environmental risks (Chaudhary et al., 2025).

One major concern involves water reuse in food processing, where non-potable water can now be used under regulated conditions. Although recent policy updates permit such practices, strict monitoring systems, advanced treatment technologies, and comprehensive risk assessments are essential to safeguard consumer health (Meneses, Stratton et al. 2017). Another significant issue arises from pesticides applied to fruits during cultivation and post-harvest handling. When bioactive compounds are extracted from fruit by-products, pesticide residues may co-extract with the target compounds, raising questions about the "natural" status and safety of these ingredients (Cegledi, 2023).Moreover, the extraction solvent can influence the concentration of pesticide residues, further complicating safety evaluations (Baele, Li et al. 2012; Vilas-Boas, Pintado et al. 2021). Although pesticide risks remain low when applied within permitted limits, responsible use must be ensured to prevent environmental and health hazards (Hasan, Islam et al. 2024). Studies also highlight broader chemical risks associated with reusing agricultural by-products, including the presence of heavy metals, veterinary drugs, and natural toxins. These contaminants can accumulate in the food chain if waste-derived materials are not carefully screened and managed. Limited data on such hazards within circular farming systems reinforces the need for precautionary measures and robust regulatory oversight(Focker et al., 2022). Ensuring the safe use of waste-derived bioactive compounds therefore requires strict quality control, validated extraction processes, and regulatory compliance to prevent potential risks to consumers and maintain food safety standards (Van Asselt, Arrizabalaga-Larrañaga et al. 2023).

II. Limitations and Challenges

Although more and more studies are dedicated to the food waste as a possible source of liquid biofuels and bioactive-containing components, the number of obstacles to the exploitation of the opportunity is high.(Guddi et al., 2025). To transform the heterogeneous food residues into reliable fuel blends, the problem of non-uniform composition, poor processes, and the best technologies of the food residues processing has to be addressed (Karmee 2016). Other more recent inventions are the introduction of nanotechnology in improving the stability of the food waste and its performance into bioactive compounds (Yadav et al., 2024). The safety concern however arises with the usage of nanoparticles. They are very small and were too large to react with the digestive enzymes thus they can influence normal metabolic functions (McClements & Xiao, 2017). Certain nanoparticles might cause oxidative stress or be deposited in certain tissues or disrupt the absorption and controlled release of bioactive molecules. This may be extended further with encapsulation of bioaccessibility to further increase the degree of toxicity by increasing the degree of exposure of level of toxicity with increasing doses of toxicity (Horie & Tabei, 2021). It is also becoming a concern that the particles may result in destabilization of the gut microbial ecosystem that is essential to the overall physiological wellbeing (Karl et al., 2018).Regardless of all these possible risks, the validated regulatory measures are not all inclusive when it comes to safety of the nano-enabled food applications, and safety is not considered holistically, and existing approval systems have loopholes (Vilas-Boas, Pintado et al. 2021). These limitations warrant the fact that improved, well-designed toxicology evaluations, free-market regulation, and accountable formulation procedures in the event of the use of bioactive substances recovered in the food waste (Weber, 2023).

III. Conclusion

As mentioned in this review, scientific and industrial interest in valorization of food waste and agro-industrial by-products as renewable sources of high-value bioactive compounds, including flavonoids, anthocyanins, carotenoids, lycopene and other phenolic antioxidants, has been increased (Saini et al., 2025). The modern extraction platforms have significantly contributed to recovery, stability and functional performance of such biomolecules and above all, the development of the modern extraction platforms, microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), co-extrusion, and other green technologies are more effective and efficient than the traditional solvent-intensive methods (Barzan, 2022). The technologies are superior in mass transfer, reduced thermal loss, reduced processing time, and energy efficiency, thus, in conformity with sustainability objectives and principles of the circular bioeconomy across the globe (Vijaya Raghavan & Kurian, 2024). Their broad use in the sector is seen in terms of incorporating recovered bioactives in functional foods, nutraceutical preparations, biodegradable packaging, and targeted delivery (Petkoska et al., 2021). Oxidation, light and temperature Co-extrusion and micro-encapsulation methods are also applied to protect sensitive molecules to ensure bioactivity and stable shelf life. Despite the above developments, several problems that impede fluency in industrial translation exist (English et al., 2023). Of great concern is the conformity to regulations, standardization of the extraction protocols, solvent safety, toxicological studies and inter-batch control. Moreover, the stability and encapsulated or concentrated bioactive structural stability is a matter that should be investigated further, particularly to the setting of various storage and processing conditions (Vega, 2020). The compliance with international standards of food safety, the strict screening of the contaminants and the effective quality-monitoring system should be ensured in order to provide the safe usage of the products by the consumers (Okpala & Korzeniowska, 2023). In the meantime, reactor design, intensification of the processes, green solvents and combined extraction-purification processes are all making such technologies more and more scalable and cost-effective (Cravotto, 2025). Altogether, the technological innovation, sustainable methods of processing, and the shift of the regulatory trends are transforming food waste, as an environmental liability, into a resource (Xiao et al., 2024). The developments will contribute largely to waste reduction, resources and development of a food/pharmaceutical system enriched with bio-active recovery and provision of high-value functional ingredients that may be applied in reduction of waste, conservation of resources and development of environmentally responsible food and pharmaceutical systems (Panda et al., 2024).

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Conflict of Interest
The authors declare that no conflicts of interest influenced the preparation or publication of this review manuscript.

Author Contributions
TK led the literature compilation and manuscript drafting. JR organized sources and contributed to critical revisions. FJ supported content development and formatting. PM provided academic supervision and final approval of the manuscript.

Data Availability
Not Applicable

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