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Recovery of valuable substances from food waste by ohmic heating assisted extraction -A step towards sustainable production

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ABSTRACT

The food sector produces immense amounts of waste daily, which is a great threat to the food system's sustainability. The great volume of waste generated by the food sector is a valuable source of different essential substances. The conversion of tonnes of waste into valuable substances by using various innovative 'green' technologies is a novel approach. Ohmic heating is a sustainable and green technology based on the utilization of electric energy, which is converted into thermal energy to heat the substance. It has wide-ranging applications in the food sector, particularly for processing i.e. as pasteurization, sterilization, blanching, extraction, and many more. It is a high energy-efficient technology, which requires less processing time and allows precise control of temperature, which makes it suitable for various purposes. Ohmic heating-assisted extraction (OHAE), an innovative approach, presents an opportunity to extract numerous valuable substances from waste materials by the application of electric current. This review provides a critical assessment of investigations centered on the recovery of various substances by the implementation of OHAE from waste materials of fruits, vegetables, poultry, fish, and cereals. The impact of various parameters used in OHAE on the effectiveness of the extraction process and yield of extracted products are discussed. The substances extracted from these waste materials encompass bioactive compounds, pectin, essential oils, proteins, and cellulose fibers, all of which find substantial applications in the food and related industries. Overall, the implementation of ohmic heating, either alone or in combination with other novel technologies, is very effective for the extraction of valuable substances from the waste of the food industries.

1. Introduction

The rapid growth of the global human population, urban sprawl, and economic progress are all driving a significant increase in food-related waste generation. By the year 2050, it is estimated that the planet will produce a substantial 3.4 billion tons of waste annually, marking a significant increase from the current 2 billion tons (Coelho et al., 2023a). Typically, this waste is left as refuse and, to a lesser degree, employed as fertilizer by farmers. The substantial volume of food waste presents environmental and economic challenges (Tunç and Odabaş, 2021). The concerning situation of producing waste pollution has encouraged researchers to focus on the efficient valorization of these waste materials (Hassani et al., 2023; Bidura et al., 2023; Al-Saeed et al., 2023). The idea of a circular economy imposed by the European Union (EU) and one of the sustainable developments goals set in 2015 by the United Nations (UN) presents a chance to recycle and reprocess agro-industrial waste into valuable products, aiming to eliminate waste disposal and promote sustainable development. This waste, which is abundant in numerous valuable compounds, can be reused to prevent environmental risks and expand the usage of these by-products as functional ingredients (European Commission, 2015; United Nations, 2015).

The food processing sector-generated waste is a rich source of

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bioactive compounds (BCs), comprising antioxidants (such as polyphenols and dietary fibers), pigments, flavors, proteins, pectin, essential oils (EOs), enzymes, gelatin, bioactive peptides and dietary fibers (Saberian et al., 2018; Torgbo et al., 2022a; Kadem et al., 2023; Maqbool et al., 2023). The next step is the processing of extraction to obtain these substances from food waste (Swantara et al., 2023). There are various conventional extraction techniques such as dry and wet rendering extraction (Al-Hilphy et al., 2022), base and acid digestion (Kadem et al., 2023), hot water extraction (Saberian et al., 2017), accelerated solvent extraction (Pereira et al., 2020), mechanical shaking and Soxhlet extraction (Torgbo et al., 2022a) are being used for the extraction processes. However, there are various shortcomings associated with these methods, including longer extraction time, higher processing temperatures, low yields, and the use of environmentally unfriendly solvents, which represent significant issues (Torgbo et al., 2022a). The limitations of traditional extraction methods have encouraged the exploration of novel alternative technologies. Furthermore, the growing environmental concerns are demanding sustainable green processing technologies. The green technologies have maximum efficiencies, use a smaller amount of chemicals or solvents, and produce less waste. In recent years, sustainable and eco-friendly approaches, including ultrasound-assisted extraction, ultra-high pressure assisted extraction, pulsed electric field (PEF) assisted extraction, ohmic heating assisted extraction (OHAE), and microwave-assisted extraction technologies, which have gained traction among researchers (Sabanci et al., 2021; Coelho et al., 2021; Çilingir et al., 2021).

Among these innovative technologies, one emerges as particularly important in food processing, which is ohmic heating or joule heating, which is based on the principles of Ohm's law and relies on electric field application. However, in contrast to ultra-high pressure or PEF, it can be differentiated by its thermal characteristics, enabling a manageable heating rate, an limited treatment duration (ranging from seconds to hours), a diverse range of waveform types and frequencies (typically sinusoidal with frequencies spanning from Hz to kHz), and the existence of alternating moderate to low electric fields (which can drop below 0.1 kV/cm) (Pereira et al., 2020). This technology attains the required processing temperature within a limited timeframe, typically just a few seconds that preserve nutritional, functional, and structural attributes of food products (Pereira et al., 2020; Çilingir et al., 2021; Torgbo et al., 2022a; Coelho et al., 2023a). Recently, researchers have demonstrated that ohmic heating has the potential to serve as an effective and eco-friendly technology. It can reduce the solvent usage, reduce the need for chemicals, shorten processing times, minimize waste generation, and reduce energy consumption (Coelho et al., 2021). It has been used in boiling, fermenting, steaming, peeling, blanching, thawing, cooking, evaporation, sterilizing, extracting, distilling, drying, and pasteurizing processes (Sabanci et al., 2021; Çilingir et al., 2021; Goksu et al., 2022; Kadem et al., 2023). OHAE is the process in which heat produced can be harnessed for the recovery of targeted components (Al-Hilphy et al., 2020). This method stands out as an efficient technique for extracting the valuable substances, as it enables a rapid, uniform, and selective extraction by applying mild electric fields across the raw material (Torgbo et al., 2022a). This process disrupts the cell membrane, leading to pore formation (electropermeabilization) or cell disintegration. As a result, it enables the diffusion of intracellular components, thereby enhancing both extraction yield and the quality of the extract (Quero et al., 2022).

2. Fundamentals of OHAE

Ohmic heating, is also recognized as electrical resistance heating or electroconductive heating, is an electrical current-based technology in which an alternating electric flow is compelled to traverse the material requiring heating. This electrical resistance generates heat, elevating the product's temperature rapidly and uniformly (Coelho et al., 2021; Çilingir et al., 2021). The generation of heat within the material can be attributed to two primary factors. First is the migration of ions in an electrolyte toward oppositely charged electrodes, and second resistance resulting from the collisions between ions, which subsequently augments their kinetic energy (Kumar, 2018). Ohmic heating systems come in a wide range of structural configurations, comprised of several key components. The fundamental elements encompass a heating chamber, electrodes, and a generator that generates alternating current to deliver electrical energy to the system (Kumar, 2018; Sharifi et al., 2022). The OHAE setup includes a power source, a temperature regulation system, two electrodes, and an extraction chamber (Al-Hilphy et al., 2020). Typically, the material is placed between two electrodes through which the electric current flows. The electric current generates heat within the material, promoting the release of target compounds from the matrix. Due to safety considerations, conductive materials cannot be used for constructing the chamber. Therefore, materials such as plastic, ceramic, glass, or any non-conductive substance are preferred for this purpose (Sagita et al., 2021). To monitor the extraction process, a custom-designed microprocessor is utilized to simultaneously record temperature, voltage, and current data (Goksu et al., 2022). In addition to these, factors such as electric field strength (EFS), electrical conductivity (EC), applied voltage (AV), frequency, waveform, temperature, and product attributes like flow characteristics, material viscosity, and particle size play a significant role in influencing the whole process and its efficiency (Sakr and Liu, 2014). Fig. 1 shows the design of the ohmic heater used for the extraction along with factors affecting its performance.

Power generation correlates directly with the square of the applied electric field (E, V/cm) and the electrical conductivity of the food (σ, S/m) (Kumar, 2018; Sharifi et al., 2022). So, the heating rate is primarily contingent on the EFS. As the EFS increases, the heating rate values was also increased (Al-Hilphy et al., 2020, 2022). EC is another crucial parameter in OHAE, and it has been thoroughly analyzed by different researchers in various applications (Çilingir et al., 2021). An increase in EC was observed with an increasing the temperature. As the temperature increased from 20 to 140 °C, the EC was increased from 0.38 to 1.47 S/m at an EFS of 5.71 V/cm. This increase can be attributed to the increase in ion mobility and reduction of viscosity as the temperature increases (Kadem et al., 2023). The AV utilized in an OHAE exerts a promising influence on the heating rate (Sagita et al., 2021). In OHAE, the heating time decreases with the higher AV (Al-Hilphy et al., 2022). The waveform and frequency of the AV also exert a significant influence on the heating rate and electrical conductivity of materials. Sinusoidal and triangular waves are much effective in augmenting the wavelengths of electricity as compared to square waves (Silva et al., 2017). When assessing the energy consumption in OHAE processes, it has been observed that energy usage can be fluctuated based on the specific process and duration of this technique when it was applied on various applications (Çilingir et al., 2021).

3. OHAE of valuable substances from food waste

3.1. Bioactive compounds (BCs)

There are various valuable substances extracted from food waste by the application of OHAE. Fig. 2 shows the common functions of these valuable products extracted from food waste. BCs are natural substances found in food, plants, and other organisms. These can be categorized into several classes, including terpenoids, alkaloids, nitrogen-containing compounds, organosulfur compounds, and phenolics (Altemimi et al., 2017; Abbas and Alkheraije, 2023; Swantara et al., 2023). Moreover, these compounds have a wide range of health benefits owing to their various properties. Among these, phytochemicals, polyphenols, and carotenoids are particularly noteworthy (Ghany et al., 2023; Azam et al., 2023). These compounds have different functions such as antioxidant, anti-cancer, anti-inflammatory, and antimicrobial activities, making them important contributors to overall well-being and health (Jha and

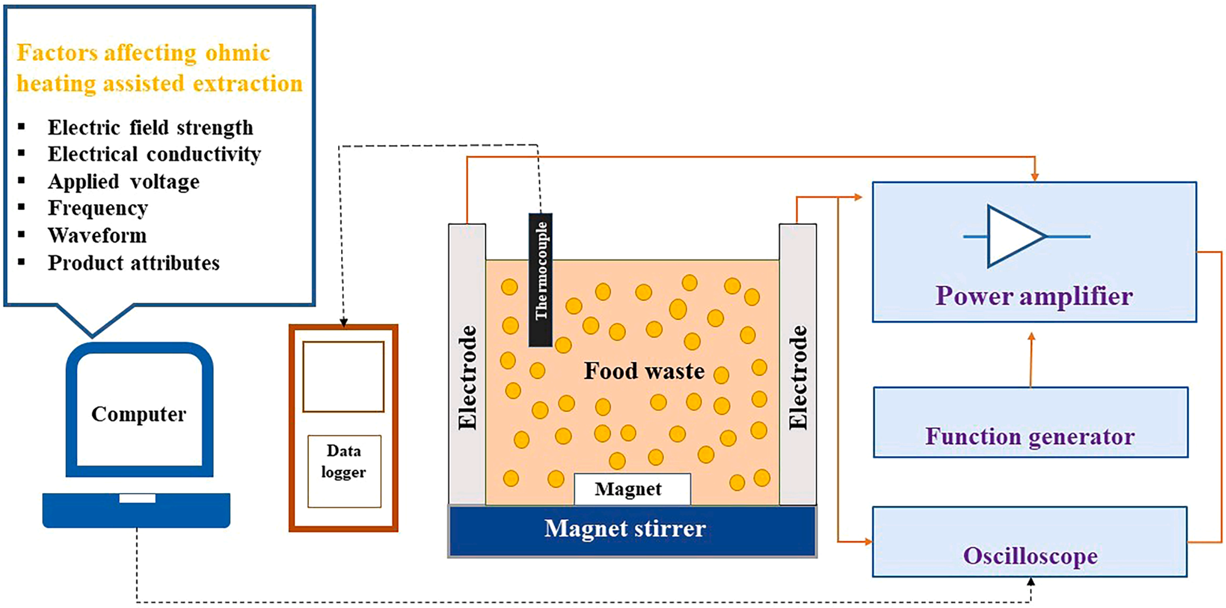

Fig. 1. The design of ohmic heater used for extraction of valuable substances from food waste and factors affecting its performance.

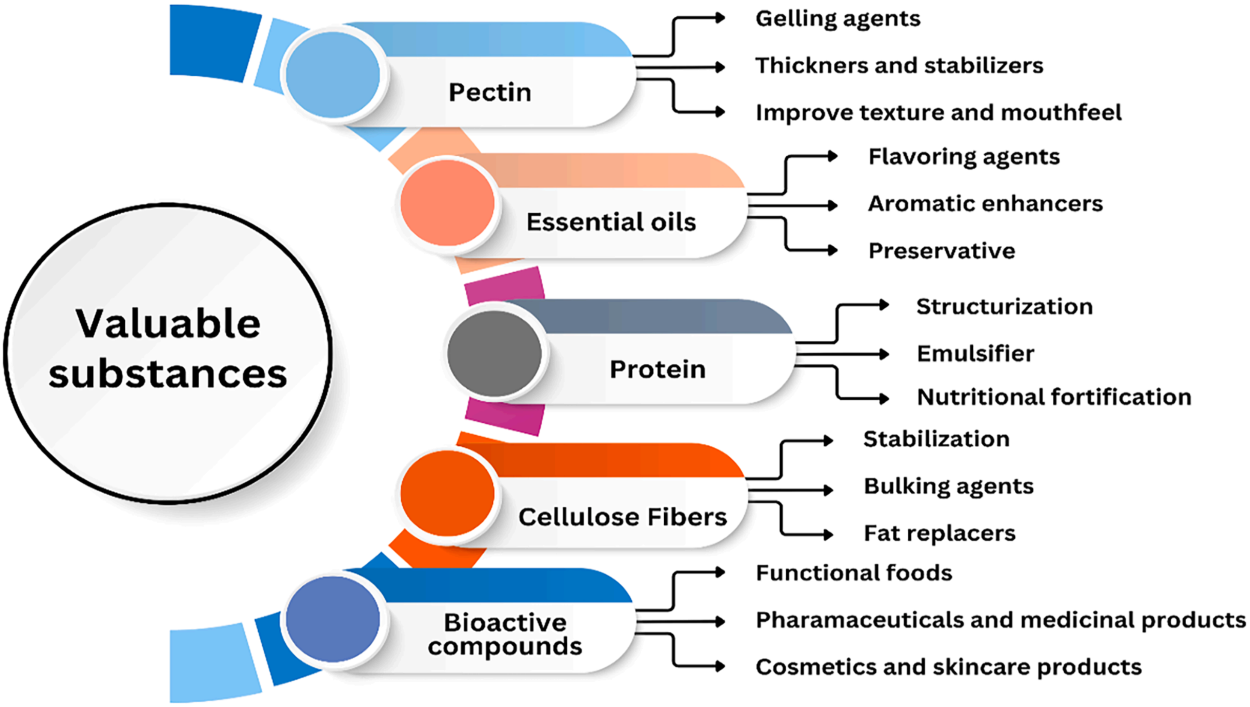

Fig. 2. The functions of valuable substances obtained from various types of food waste.

Sit, 2022; Abduallah et al., 2023; Saleh et al., 2023). Many research investigations have been carried out so far to extract BCs from food waste using OHAE.

Coelho et al. (2021) focused on the recovery of anthocyanin from wine-making by-products through OHAE and compared it with conventional techniques (CTs), employing food-grade solvents, primarily water. The process was carried out at 30 V/cm and results indicated that OHAE provided higher levels of total phenolic content (TPC) (3.3 mg/g) and ascorbic acid (2.3 g/100 g). In CTs, TPC has values of 2.5 g/100 g and ascorbic acid has values of 2.2 g/100 g. These were some types of anthocyanins found in the extracts obtained by OHAE. It exhibited higher recovery yields of anthocyanins compared to CTs, along with the benefits of shorter treatment times, decreased energy consumption, and the absence of harmful solvents. Moreover, the obtained extracts demonstrated high antibacterial and antioxidant activity as compared to extracts obtained by using CTs. In a study, Torgbo et al. (2022a) used OHAE to extract the phenolic compounds from rambutan peels. In this process, deionized water and ethanol solutions with different concentrations were used as the electrical transmission mediums and the extraction was done at different holding durations (15, 30, and 60 min). The obtained results showed prominent change between the water-based and ethanol-based extracts in terms of extraction yield, TPC, total flavonoid content (TFC), and antioxidant activities. The gallic acid, corilagin, geraniin, and ellagic acid were the main compounds found within peel extracts. In another research Al-Hilphy et al. (2020) investigated the pilot-scale OHAE process, utilizing a polar solvent with 0.1 % NaCl, for extracting BCs from wheat bran. Three different EFS (4.28, 7.90, and 15.71 V/cm) were tested. This method resulted in a 63 % reduction in energy consumption as compared to traditional extraction techniques. The OHAE extracts exhibited higher quantities of BCs and stronger antioxidant properties (antioxidant effectiveness ranging from 56 to 84 %). Incorporating this extract prolonged the shelf life of corn oil from 11 to 26 days, which can effectively retard the oxidation process. In another study, Loypimai et al. (2015) examined the extraction of BCs from rice bran using OHAE. The 50–200 V/cm of EFS was employed on the cereal waste for better efficiency. The results suggested that OHAE is a highly promising technique, delivering both substantial yields and concentrations of BCs. The highest levels of BCs were found in the colorant powder extracted from the bran using OHAE with 30 % moisture content (EFS of 100–200 V/cm) and 40 % moisture content (EFS of 50, 100, 150, and 200 V/cm).

Pereira et al. (2020) implemented the OHAE on grape skins' winemaking residues as natural conductors of electricity to obtain anthocyanins. The mild temperature at 40 °C for 20 min and the other employ rapid heating from 40 to 100 °C for 20 s. Irrespective of the temperature used, the OHAE treatment significantly improved the extraction levels, resulting in elevated concentrations of TPC, enhanced conductivity, increased soluble solids, and intensified red color of the extracted compounds. The application of high-temperature short-time, ohmic heating pretreatments, marked by the rapid and efficient internal heating of grape skin structures resulted in a significant increase in the overall concentration of anthocyanins, elevating it from the baseline level of 756 to 1349 μg/g.

Quero et al. (2022) conducted research on olive pomace, which is a primary byproduct of the olive oil production industry. The extracts were obtained through both OHAE and conventional heating (CH) methods, employing water and 50 % ethanol. Upon careful chemical analysis, it became apparent that the ohmic-hydroethanolic extract demonstrated prominent antiproliferative effects. This can be primarily attributed to its significantly higher phenolic compounds as compared to other extracts. Hence, the BCs extracted from olive pomace through OHAE technology hold a significant potential for applications in the food, nutraceutical, and biomedical industries. Erol (2022) recovered polyphenols from industrial chestnut peel waste utilizing OHAE. Through RSM, they determined the optimal pretreatment conditions (20 V/cm, 100 s), and a salt concentration of 0.32 %. The authors found that the polyphenol content and antioxidant capacity of the peel extracts were influenced by the chestnut variety and the extraction solvents used. Ellagic acid was the predominant phenolic compound across all varieties. The pretreatment enhanced the extraction process. Furthermore, alcoholic extraction was more effective in recovering polyphenols compared to water. In another study Coelho et al. (2023a) implemented OHAE and conducted a comparative analysis with CH for the retrieval of various compounds from tomato processing residues. The tomato processing by-products they utilized were discovered to possess significant protein content (ranging from 16 to 19 g/100 g), high fiber content (ranging from 57 to 59 g/100 g), and a fatty acid presence (about 17 g/100 g). Analysis of the extract indicated its predominant components to be chlorogenic acid and rutin, both belonging to the category of phenolic compounds. With a deeper understanding of the composition of these by-products, the researchers applied OHAE to find added-value solutions for these tomato processing wastes. The treatment yielded two distinct fractions from the tomato processing by-products: a liquid fraction, characterized by high contents of phenols, free sugars, and carotenoids, and a solid fraction rich in fibers bound to phenols and carotenoids. The advantage of this treatment was its ability to preserve carotenoids, particularly lycopene, in contrast to CTs.

3.2. Pectin

Pectin, a heteropolysaccharide, is a naturally occurring substance obtained from various fruits and vegetables. In the food industry, it serves as a dietary fiber, a thickening agent, and a gelling agent. Pectin on the degree of esterification of its carboxylic acid groups, is classified into two types which are high methoxyl pectin and low methoxyl pectin. It contains esterified groups and neutral sugars as side chains, creating various covalently connected components (Hosseini et al., 2019). There are various studies conducted so far on pectin extraction from food waste by applying OHAE.

Sabanci et al. (2021) employed OHAE to extract pectin from grapefruit, lemon, and orange waste samples at 80 °C, at various processing times. The EC value was measured between 1.46 and 2.06 S/m during heating. The total energy consumption was noted to rise with extended processing times. This process involved extended treatment at specific pH and temperature conditions and yielded approximately 9–14 % pectin from the waste, with processing time variations. Analogous findings have been reported by Goksu et al. (2022) who employed grapefruit peel powder for pectin extraction using OHAE. The authors further explored the quality of the extracted pectin under different conditions. The authors conducted experiments with varying EFS (7 to 11 V/cm), solid-to-liquid ratios (1:20 to 1:60), and holding times (0 to 180 min) while keeping the pH and temperature constant at 80 °C. The maximum specific pectin production coefficient recorded was 15.63 ±1.59 mg/kJ, achieved at an EFS of 11 V/cm, with an energy consumption of 35.01 kJ during a 180 -min extraction period. The investigation revealed that the peak energy efficiency values were 89.47 % and 56.02 %, whereas exergy efficiency values, although lower, reached 73.69 % and 18.09 %. In another study, Çilingir et al. (2021) extracted pectin from lemon peel powder using ohmic heating and assessed the specific pectin production coefficient (mg/kJ). This coefficient was then compared with the traditional pectin production. The researchers carried out the extraction process at three distinct temperatures (ranging from 70 to 90 °C), three diverse solid-to-liquid ratios (ranging from 1:30 to 1:50 g/mL), and three varying extraction holding times (ranging from 0 to 30 min). Throughout these experiments, they kept the pH constant. The investigation unveiled that with higher temperatures and longer extraction durations, the pectin yields exhibited an upward trend, ranging from 4 to 11 mg/kJ.

Sharifi et al. (2022) investigated the pectin recovery from pomegranate peel using the OHAE method. The objective was to assess and compare the properties of this pectin with those obtained from the conventional acidic extraction method under optimal conditions. The optimal conditions for the OHAE method were found to be an EFS of 10 V/cm and a processing time of 18 min. In these specific settings, the OHAE process yielded 8 % of the extract, with a high galacturonic acid content of 82 %. In contrast, conventional methods yielded an 8 % extract with a galacturonic acid content of 73 %. Saberian et al. (2018) investigated the impact of EFS, pH, and solid-to-liquid ratio on the heating rate, system performance coefficients, yield, and pectin quality during OHAE up to 90 °C. The results revealed a substantial increase in pectin yield, ranging from 1.17 to 10 g/100 g dry matter, as the pH decreased from 4 to 1.5. The optimal conditions for obtaining the highest SPC and pectin yield with excellent quality were as follows a 30 V/cm EFS, 1.5 pH, and a 1: 20 g/mL solid-to-liquid ratio. In the study conducted by Saberian et al. (2017) they concentrated on the extraction of pectin from waste of orange juice with the implementation of OHAE. Their investigation revolved around evaluating the influence of EFS, temperature, and processing time on factors such as pectin yield, galacturonic acid content, and the degree of esterification of the pectin. The findings from their research demonstrated that the greatest pectin yield, amounting to 14 g/100 g was obtained by employing the optimal conditions, which encompassed an EFS of 15 V/cm, and a processing temperature of 90 °C for a duration of 30 min. Under these specific conditions, the pectin displayed an emulsifying activity of 67 %, which was comparable to conventionally extracted pectin. Furthermore, the emulsions remained stable at levels between 91.88 % and 94.87 % after 30 days of storage. In another study, Sengar et al. (2020) applied five different extraction techniques, to extract pectin from tomato waste. The OHAE was coupled with ultrasound technology and the primary objective of this study was to investigate the extraction and degradation kinetics, ultimately optimizing the pectin extraction process. The results unveiled a diverse range of pectin yields, spanning from 9.30 % for OHAE coupled with ultrasound. It is worth noting that all pectin extracts obtained under optimal conditions exhibited satisfactory purity levels, featuring a galacturonic acid content ranging from 675 to 913 g/kg of pectin.

3.3. Oils

Oils derived from carp viscera, often referred to as fish oils, are renowned for their high nutritional content. These oils represent a rich source of ω−3 polyunsaturated fatty acids, which are known to offer a multitude of health benefits. They can enhance the functioning of the heart, brain, and immune system, among other positive effects on human health (Rahimi et al., 2021; Radwan et al., 2022; Bangulzai et al., 2022). Al-Hilphy et al. (2022) introduced OHAE to obtain of oil from carp viscera, a by-product of seafood processing. The study conducted by researchers aimed to assess how various temperatures (75 ℃, 85 ℃, 95 ℃) and EFS (7, 9, 22 V/cm) would affect the system's performance and the physicochemical properties of the extracted oil. OHAE demonstrated several advantages, including a 94.46 % reduction in specific energy consumption compared to CH and a substantial decrease in extraction time, from 72 to 30 min. OHAE also led to improvements in color values and a reduction in peroxide (13 %), free fatty acids (44 %), and thiobarbituric acid (93 %), respectively. The highest system performance, productivity, and oil yield were achieved with an EFS of 22 V/cm and a temperature of 95℃. The study not only effectively utilized carp viscera but also contributed to the production of a value-added product while enhancing the process's environmental sustainability by 50.08–69.07 %. EOs are aromatic substances mainly obtained from various parts of plants and they have various applications. Every EOs has distinct properties, such as antibacterial, moisturizing, and medicinal effects, as well as a unique fragrance, which can be citrusy, spicy, floral, or herbal. The utilization of EOs has significantly broadened, moving beyond specialized laboratories to become readily accessible to the general public through pharmacies and herbal stores (Kowalski et al., 2019; Kandil et al., 2024). Tunç & Odabaş (2021) obtained pectin and EOs from citrus waste using the OHAE method followed by hydrodistillation. The research team successfully determined the ideal conditions for the process. These conditions involved using a liquid-to-solid ratio of 8.7:1, a total extraction and hydrodistillation time of 58.4 min, and an EFS of 14.2 V/cm. In these specified conditions, the pectin yield reached 16.58 g/100 g, while the EOs yield was 3.62 g/100 g. This investigation highlighted the influence of all the independent variables on the yields of both pectin and EOs. Importantly, the yields obtained using OHAE were significantly higher than those achieved through conventional extraction techniques.

3.4. Protein

Proteins are essential components of biological systems. When we consume foods rich in proteins, they provide the necessary amino acids for building muscle proteins and supporting overall body growth, making them crucial for human nutrition (Mehmood et al., 2023). These complex molecules are comprised of lengthy chains of amino acids. Proteins serve as essential macronutrients and serve various functions, including acting as emulsifying agents, binding agents, and foaming agents (Kang et al., 2021; Akhtar et al., 2023). For the extraction of amino acids from poultry slaughter waste Kadem et al., (2023b) introduced an innovative approach that combines OHAE and subcritical water. The researchers investigated the impact of OHAE under various EFS including 5.71, 7.14, and 8.57 V/cm, and treatment durations spanning 15, 30, and 45 min. They compared these ohmic heating treatments with the control method, which involved subcritical water with CH at a temperature of 140 °C. The specific energy consumption was notably reduced to 403.68 kJ/kg, a 59.22 % decrease as compared to control. The highest energy efficiency reached 93.88 % at an EFS of 8.57 V/cm, outperforming the control treatment's efficiency of 47.13 %. Recovering total amino acids at an EFS of 8.57 V/cm surpassed the control method by 70.48 %. The highest recovery efficiency of amino acids, reaching 79.40 %, occurred at an EFS of 5.71 V/cm, in contrast to the control treatment's efficiency of 15.48 %. In another study, Coelho et al. (2023b) applied OHAE to red and white grape pomace to extract different substances. The red grape bagasse exhibited a sugar content of 21.91 g/100 g, whereas the white grape bagasse contained 11.01 g/100 g of sugar. Additionally, the protein content for the red grape bagasse was measured at 12.46 g/100 g, and for the white grape bagasse, it was slightly higher at 13.18 g/100 g. OHAE demonstrated a greater antioxidant capacity compared to CTs.

3.5. Cellulose fibers

Cellulose fibers are complex polysaccharides, and they are the main component of plant cell walls. Cellulose fibers offer distinct advantages over cotton, characterized by their cleanliness, high hygroscopicity, and suitability for use in hygiene and medical products. These fibers exhibit versatile morphological and physical properties, boasting softness, excellent processing attributes, effective liquid transport capabilities, and robust mechanical properties (Brodnjak et al., 2018). In a study, Torgbo et al. (2022b) investigated electrothermal pretreatment techniques to obtain cellulose fibers from rambutan peel. This process involved utilizing OHAE under specific conditions, including a solid-to-liquid ratio of 1:10 (w/v), using a water/ethanol mixture in equal parts as the electrical transmission medium, and maintaining a temperature of 60 °C for various holding durations (15, 30, and 60 min). The application of this technique did not bring about a significant change in the total fiber yield across different holding times. Nevertheless, it had an impact on the composition of the samples, affecting extractives, lignin, hemicellulose, and α-cellulose content. Among the various pretreatment times, OHAE treatments lasting 15 and 30 min showed the most promise. They led to a reduction in the need for bleaching chemicals and an increase in the α-cellulose yield. Table 1 presents the details of conditions used for the extraction of valuable compounds from food waste by OHAE.

4. Drawbacks and challenges

OHAE is an efficient thermal technology (environment friendly), which offers several advantages over the traditional methods for food waste valorization. Its rapid and uniform heating facilitates the efficient extraction of valuable compounds, thereby reducing processing time and energy consumption (Coelho et al., 2023b). It employs volumetric heating, which minimizes localized hot spots and potentially reduces the degradation of heat-sensitive compounds present in the extracts (Coelho et al., 2021, 2023a). Nevertheless, specific challenges must be addressed for the successful industrial implementation of food waste recovery applications.

The selection of the most appropriate food waste streams for OHAE is an essential step. While it holds potential for various applications, materials with low EC, such as carp viscera, may require additional pretreatment steps (incorporation of salts and minerals or reduction of its particle size) or alternative extraction methods to enhance conductivity

Table. 1
Conversion of food waste into valuable products by ohmic heating.

Food items	Waste products	Treatment conditions	Valuable products obtained	Overall findings	References
Fruit	Grape pomace	Sample = 2.5 g, EFS = 30 V/cm, and time = 20 min	BCs	The maximum TPC recorded was 423 mg/100 g and highest concentration of anthocyanins, reaching 224.06 µg/g DW, was obtained through OHAE using water acidified with citric acid	(Coelho et al., 2021)
	Rambutan peel	Sample = 10 g, deionized water = 50 %, ethanol solution = 70 %, EFS = 200 V/cm, and time = 15, 30, 60 min		In these obtained extracts, the highest amounts of specific compounds were observed: gallic acid (4.527 mg/g) with water at 15 min, corilagin (95.339 mg/g) with 70 % ethanol at 15 min, geraniin (370 mg/g) with 50 % ethanol at 60 min, and ellagic acid (27.847 mg/g) with 70 % ethanol at 15 min	(Torgbo et al., 2022a)
	White and red grape bagasse	Sample = 2.5 g, EFS = 1–10 V/cm, and time = 10 min		Free phenolic compounds obtained from white grape bagasse (68 µg/g) and red grape bagasse (198.35 µg/g)	(Coelho et al., 2023b)
	Grape skin	Sample = 1.5 g, EFS = 16 and 80 V/cm, frequency = 25 kHz, T = 40 °C and 100 °C and time = 20 min and 3 s.		The OHAE at 100 °C resulted in extraction yield of 600 µg/g of anthocyanins from fruit waste.	(Pereira et al., 2020)
	Olive pomace	Sample = 2 g, ethanol = 20 mL, EFS = 4 V/cm, frequency = 25 kHz and T = 83 °C		The extraction yield of 28 % was obtained through OHAE, with a TPC of 17.6 mg GAE/g	(Quero et al., 2022)
	Chestnut peels	Sample = 5 g, EFS = 20 V/cm, time = 100 s, and Salt concentration = 0.32 %		The obtained extracts contained a high concentration of polyphenols, especially ellagic acid	(Erol, 2022)
Cereal	Black glutinous rice bran	Sample = 20 g, solvent = deionized water and EFS = 50–200 V/cm		At EFS of 200 V/cm, the highest level of bioactive compounds (anthocyanins) 20.67 % obtained	(Loypimai et al., 2015)
	Wheat bran	Sample = 500 g, salted water = 1500 mL, EFS = 4.28, 7.90, 15.71 V/cm and time = 4, 6, 12 min		The highest concentration of total phenolics (460 µg/mL of extract) was achieved at EFS of 15.71 V/cm	(Al-Hilphy et al., 2020)
Fruit	Lemon waste	Sample = 28.60 g, citric acid solution = 250 mL, EFS = 10, 15, 20 V/cm, and time = 30, 45, 60 min	Pectin and EOs	The maximum pectin yield recorded was 16.58 g/100 g DW at 10 V/cm for 60 min. Simultaneously, the highest EOs yield reached to 3.79 g/100 g DW at 20 V/cm for 60 min.	(Tunç and Odabaş, 2021)
	Grapefruit peel	Sample = -, EFS = 7, 9, 11 V/cm, t = 0 –180 min and T = 80 °C	Pectin	The highest specific pectin production coefficient (14.60 mg/kJ) was recorded at EFS (9 V/cm) at 180 min	(Goksu et al., 2022)
	Lemon peel powder	Sample in citric acid solution = 150 mL, EFS = 18 V/cm, time = 0, 15, 30 min and T = 70, 80, 90 °C		The highest pectin yield (16 %), recorded at 30 min with a solid-liquid ratio of 1:40 on 90 °C.	(Çilingir et al., 2021)
	Pomegranate peel	Sample = 1 g, water = 40 mL, EFS = 6. 758, 8, 11, 14, 15 V/cm, and time = 4.067, 8, 17.5. 27, 30 min		The highest extraction yield (8.16 %) was obtained with a EFS of 10 V/cm for 17.5 min.	(Sharifi et al., 2022)
	Grapefruit, orange, and lemon waste	Sample: sulfuric acid = 1:40 g/mL, EFS = 9 V/cm), T = 80°C and time = 0, 5, 15, 30, 60, 120, 180 min		The highest yield of pectin obtained from peel powder of grapefruit was 18.08 %, orange 18.32 % and lemon 14.06 % at 180 min.	(Sabanci et al., 2021)
	Orange juice waste	Sample = 30 mL, EFS = 7–15 V/cm, T = 50–90 °C and time = 5–30 min		The highest yield of pectin (14.32 g/100 g DW) was achieved with EFS (7 V/cm) at 17.5 min	(Saberian et al., 2017)
	Orange Juice waste	Sample = 50 mL, EFS = 5, 10, 15, 20, 25, 30 V/cm, solid-liquid ratios of 1:10 to 1:40 g/mL and T = 90 °C.		The specific pectin production coefficient ranged between 49 and 84 % at these parameters	(Saberian et al., 2018)
	Tomato peel	Sample = 100 g, EFS = 40, 50, 60 V/cm, time = 1–8 min, ultrasound power = 450, 600, 750 W for 2–16 min		OH-assisted extraction yielded a maximum of 10.65 % pectin at 60 V/cm. However, when combining ultrasound and OHAE at 450 W and 60 V/cm, the pectin yield was increased to 14.60 %	(Sengar et al., 2020)
Meat	Poultry waste	Sample: Water = 1:2, EFS = 5.71, 7.14, 8.57 V/cm, time = 15, 30, 45 min and T = 140 °C.	Amino acids	The highest recovery of amino acids (79.40 %) was achieved with a EFS of 5.71 V/cm, in comparison to the control group (15.48 %).	(Kadem et al., 2023)
Fruit	Tomato waste	Sample = 2.5 g, ethanol 30 %, v/v = 25 mL, EFS = 60 V/cm, and time = 15 min	Protein, fiber, fat, minerals, carotenoids	The obtained yields were as follows: fiber (590 g/kg), protein (195 g/kg), fat (178 g/kg), minerals (30 g/kg), and carotenoids (4 g/kg).	(Coelho et al., 2023a)
Meat	Carp viscera, a seafood processing by-product	Sample = 250 g, EFS = 7, 15, 22 V/cm, T = 75, 85 and 95°C, T = 7–200 min	Oil	The study demonstrated that the highest oil yield (19.67 %) was obtained at an EFS of 22 V/cm at 95 °C	(Al-Hilphy et al., 2022)
Fruit	Rambutan peel	Sample = 10 g, EFS = 450 V/cm, current = 2A, T = 60 °C and time = 15, 30, 60 min	Cellulose fiber	The highest yield of fibers (61.1 ± 0.8 %) was obtained at 60 min	(Torgbo et al., 2022b)

EFS: Electric field strength, TPC: Total phenolic content, DW: Dry weight, OHAE: Ohmic heating assisted extraction, T: Temperature.

and oil recovery efficiency (Al-Hilphy et al., 2022; Waziiroh et al., 2022; Coelho et al., 2023b). The presence and concentration of solids in the solution can affect the efficiency of ohmic heating. As concentration increases, the heating rate might decrease due to higher resistance in the solution. Optimizing factors like particle size and concentration of waste samples can be crucial for efficient process (Goksu et al., 2022; Waziiroh et al., 2022). OHAE led to a higher yield of valuable compounds (carbohydrates, ash, fiber, and protein) in the liquid fraction as compared to the solid fraction, the method's heating rate may be slower due to the presence of solids (Coelho et al., 2023a). The selection of solvent is pivotal in OHAE. While it promotes "green extraction" by favoring food-grade solvents such as water, the solvent's conductivity markedly influences efficiency. Low-conductivity solvents restrict the temperature rise during ohmic heating, potentially diminishing extraction yield. Water, with its high conductivity, emerges as an optimal choice for OHAE, as it efficiently converts electrical energy into thermal energy, facilitating effective extraction (Coelho et al., 2021; Torgbo et al., 2022a). Although it is a rapid process, which has been observed that a longer interaction time between the waste and solvent results in higher extraction yields (Torgbo et al., 2022a). Its versatility enables its combination with other innovative extraction techniques to tackle the challenges related to temperature sensitivity. A study by Kadem et al. (2023b) has been successfully integrated OHAE with subcritical water, while Sengar et al. (2020) investigated the combination of OHAE with ultrasound treatment. These synergies present promising opportunities for optimizing the extraction efficiency while maintaining the integrity of heat-sensitive compounds in food waste (Çilingir et al., 2021). The energy-intensive nature of processes on a large industrial scale highlights the importance of utilizing renewable and sustainable energy sources to mitigate environmental impacts. It presents notable advantages in terms of energy consumption. In contrast to traditional methods relying on external heat sources, it utilizes the food waste itself as an internal heat source. This eliminates the necessity for water as a heat transfer medium, resulting in a more efficient process. OHAE showcases energy consumption levels comparable to pulsed electric field (PEF) treatments, particularly at elevated temperatures. However, it may offer an additional benefit in situations where PEF is employed at high temperatures with moderate electric fields, as OHAE has the potential to achieve similar outcomes with lower overall energy consumption (Pereira et al., 2020). Not all food waste is equally suitable for it due to various factors discussed above. However, studies have demonstrated promising results, with poultry waste valorization achieving protein recovery efficiencies of up to 79.40 % (pilot scale), and citrus by-products yielding pectin extraction efficiencies ranging from 10 % to 20 %. These high extraction efficiencies underscore its effectiveness in recovering valuable resources from food waste (Çilingir et al., 2021; Sabanci et al., 2021; Kadem et al., 2023). Presently, OHAE systems used in research settings must be adapted for large-scale processing of food waste. This adaptation may involve optimizing equipment design to accommodate higher volumes and ensure efficient energy utilization. Implementing automation, robotics, and advanced technologies can enhance the efficiency and output of ohmic heating systems, contributing to more sustainable and eco-friendly practices in industrial applications. This approach aligns with the broader goal of minimizing the environmental footprint associated with various industrial processes (Meneses-Espinosa et al., 2023).

5. Conclusion

OHAE emerges as a promising green technology for transforming food waste into valuable products. As the demand for sustainable development continues increasing, this technique is expected to play a significant role in the valorization of waste materials compared to CTs. It offers numerous advantages: rapid and uniform heating, minimized localized hot spots, and the potential for green extraction using food-grade solvents like water. Research has shown the effectiveness of this technique in extracting valuable compounds such as BCs, pectin, EOs, proteins, and cellulose fibers from various food waste streams. These extracted components have diverse applications across industries, contributing to the development of a circular bioeconomy. To enable widespread industrial adoption, it is crucial to address challenges associated with it. This involves scaling up OHAE systems to efficiently handle larger volumes of food waste, enhancing economic feasibility through cost-effective approaches and alternative electrode materials, and identifying the most suitable food waste streams. Additionally, potential pre-treatment steps should be explored to optimize conductivity for efficient extraction. A promising strategy to overcome challenges and improve the effectiveness of it, is its integration with other green technologies. Research investigating synergies with subcritical water extraction, ultrasound technology, and pulse electric field techniques illustrates this potential. Further exploration and experimentation in this domain can pave the way for innovative and efficient food waste valorization processes. Future research endeavors should prioritize two critical areas: conducting life cycle assessments to evaluate OHAE's environmental impact relative to traditional methods and integrating it with renewable energy sources to further reduce its environmental footprint. By addressing these research gaps and focusing on overcoming challenges for industrial adoption, OHAE holds the potential to revolutionize sustainable food waste management. This green technology has the capability to significantly contribute to a circular bioeconomy by extracting valuable resources from food waste streams.

Ethical statement

This work does not involve animal or human studies for experimentation.

Ethical Approval

Not Applicable.

CRediT authorship contribution statement

Samran Khalid: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Syed Ali Hassan:** Methodology, Conceptualization. **Ammar B. Altemimi:** Writing – review & editing. **Kashmala Chaudhary:** Writing – review & editing. **Sumbal Raana:** Writing – review & editing, Writing – original draft, Data curation. **Hamza Javaid:** Visualization. **Muhammad Naeem:** Writing – review & editing, Supervision. **Zuhaib F. Bhat:** Writing – review & editing, Formal analysis. **Rana Muhammad Aadil:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflicts of interest.

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