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DOI:
10.1186/s43014-023-00162-z

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Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Al-Najjar, SZ, Al-Sharify, ZT, Onyeaka, H, Miri, T, Obileke, K & Anumudu, CK 2023, 'Advances in mass transfer and fluid flows in non-thermal food processing industry: a review', *Food Production, Processing and Nutrition*, vol. 5, no. 1, 50. https://doi.org/10.1186/s43014-023-00162-z

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Al-Najjar *et al.*
Food Production, Processing and Nutrition (2023) 5:50
https://doi.org/10.1186/s43014-023-00162-z

Food Production, Processing and Nutrition

REVIEW

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Advances in mass transfer and fluid flows in non-thermal food processing industry – a review

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Abstract

All around the world, food processing techniques make use of various kinds of treatments to improve the shelf-life of foods. The commonly used thermal treatments are likely to result in deteriorating the sensory as well as nutritional qualities of foods. However, consumers are now demanding for safer and cleaner food without needing to compromise on the quality. Owing to the evolving nature of consumer demands, food technologists and others in the agro-food chain have devised processes to meet these changing demands by considering new non-thermal food processing techniques, which achieve microbiological inactivation in food materials without the application of heat directly. This review provides an appraisal on certain non-thermal food processing technologies with a focus on their operational mechanisms and success in the preservation of numerous kinds of food and offers an outline on the developments in non-thermal food processing techniques used in the food industry to enhance mass transfers. Increase in mass transfer is of industrial interest owing to a reduction in operation time. Use of a faster mass transfer velocity in the process produces multiple benefits, such as an increase in productivity, the preservation of physiological and nutritional value of food components, and a reduction in economic costs. The review demonstrates that techniques such as Pulsed Electric Field, Ultrasonication and Supercritical technology are viable treatments for enhancing mass transfer in the food processing industries.

Keywords Non-thermal food processing, Mass transfer, Food preservation, Fluid flow, Pulsed electric field (PEF), Ultrasonication, Supercritical technology

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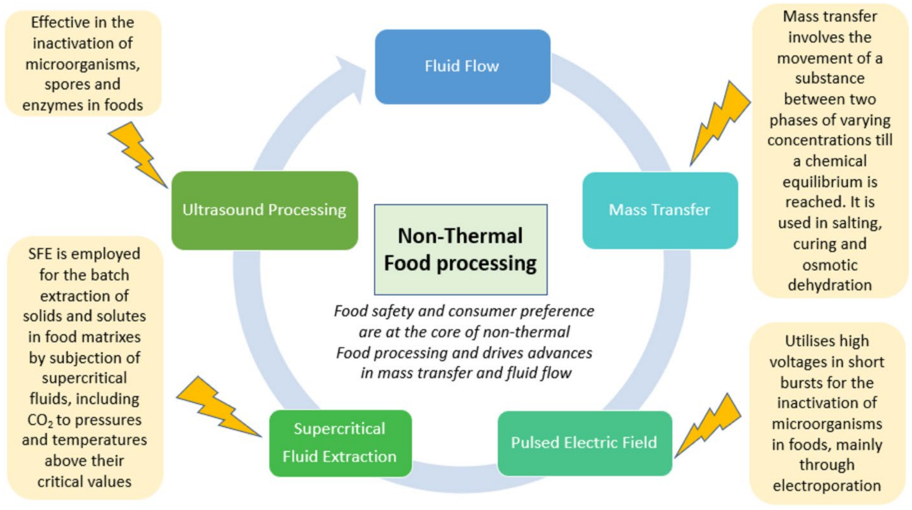
Graphical Abstract



Introduction

From early on, food processing technologies have focused on guaranteeing the safety of foodstuffs and prolonging their shelf-life. Recently, authors tempt to develop stainable food systems in optimal food availability, retention, and production (Gould 2011; Hendrickx & Knorr 2002; Bellisle 1998; Knorr 1983, 2003). A wide number of diverse changes have been made to food processing technologies since then, especially within the agro-food industry (Roobab et al. 2018; Peña et al. 2019; Troy et al. 2016; Hernández-Hernández et al. 2019). In the agro-food chain, consumers are key. Their demand for fresh and nutritious foods with longer shelf-lives has increased over the years. Owing to the evolving nature of consumer demands, food technologists and others in the agro-food chain have devised processes to meet these changing demands (Hernández-Hernández et al. 2019).

The primary method for treatment of microbiological stabilization and sensory and nutritional property preservation for many years have been largely associated with heat (Knockaert et al. 2012; Zhong et al. 2019). Whilst the key aim of food processing is to reduce pathogenic microorganisms in food and food spoilage by extension, heat adversely affects both sensory characterises and nutrient contents of foods, resulting in a change in the foods physico-chemical attributes which affects both the organoleptic quality and can result in the breakdown of key nutrients within the food. Some of these unwanted and undesirable affects because of heat processing technologies are modifications in the concentration of thermo-sensitive bioactive compounds in food, nutrient content, appearance, texture and sensory characteristics of food. The drive for innovative non-destructive food technologies, therefore, can be attributed to an increased consumer demand for the preservation of nutritional contents and desirable sensory qualities in food (Hernández-Hernández et al. 2019; Valdramidis & Koutsoumanis 2016). These non-destructive technologies are designed to retain the sensory aspect of food whilst ensuring microbial inactivation (Bhattacharjee et al. 2019; Bahrami et al. 2020).

Heat processing eliminates microorganisms and affects food's physical, sensory, and nutritional properties. Customer demand and this assumption have motivated technology advancement. Furthermore, improvements in medicine, biology, nutrition, nutrigenomics, and food processing have led to various functions that need individual conditioning and preservation procedures to preserve their bioactive components. Non-thermal food preparation is typically recommended for safe, nutritious, and flavorful meals. Pulsed electric field technology, an unique non-thermal food processing procedure that degrades nutrients and tastes less than drying, pasteurization, sterilization, solvent extraction, and heat-sensitive foods like fruit juices and smoothies, has expanded in commercial applications. Lab- and pilot-scale equipment become industrial-scale. Several publications confirm that PEF-treated fruit juices and smoothies are available in various nations (Hernández-Hernández et al. 2019).

New non-thermal food processing techniques, which achieve microbiological inactivation in food materials without the application of heat directly (Troy et al.

2016; Hernández-Hernández et al. 2019; Bhattacharjee et al. 2019), are emerging and novel alternatives to the conventional thermal processing techniques (Hernández-Hernández et al. 2019; Chemat, Rombaut, Sicaire, et al. 2017). These newer methods, yet to replace their conventional counterparts, include pulse electric fields (PEF), non-thermal plasma / cold plasma (NTP), pulsed light, ultrasound technology (Rahaman et al. 2016; Dong et al. 2021), ozone treatment (Guzel-Seydim et al. 2004; Komanapalli & Lau 1996; O'Donnell et al. 2012), and high-pressure processing (HPP) (Zhong et al. 2019). Ionizing radiation, ultrasound, pulsed light, ultraviolet radiation, HPP, and PEF technologies are classified as physical processes whereas cold plasma and ozone technologies are classified as chemical processes (Guzel-Seydim et al. 2004; Komanapalli & Lau 1996; O'Donnell et al. 2012; Rahaman et al. 2016; Dong et al. 2021).

As mentioned earlier, non-thermal food processing technologies involve ultrasound technology, cold plasma (non-thermal plasma), ozone treatment, high-pressure processing (HPP), ionizing irradiation (IOR), ultraviolet radiation (UV), pulsed light (PL) and pulsed electric field (PEF) (Chacha et al. 2021). Non-thermal techniques may increase food quality and yields alone or with other strategies. Maximizing energy and mass transfer, mixing components, conserving food properties, and decreasing heat and concentration gradients improve filtration, freezing, separation, drying, emulsion, thawing, brining, oxidation, homogenization, meat tenderization, sterilization, and extraction. Ultrasounds increase drying kinetics, saving energy and time. Hydrophilic nutrients and chemicals are better at mass and energy transfer, mixing, food characteristics, and decreasing temperature and concentration gradients, therefore, they are less likely to be lost if the product is not immersed. Ultrasounds before drying typically increase drying kinetics, reducing drying time. In addition, ultrasonic technology inhibits browning enzymes by rupturing cell membranes, which has garnered attention. Chiozzi et al. 2022 compared thermal (pasteurization, sterilization, and aseptic packing) and non-thermal (ultrasounds, UV radiation, ozonation, and high hydrostatic pressure) food preparation procedures (Chiozzi et al. 2022; Al-Sharify et al. 2020). They investigated ultrasounds application in Fruits and Vegetables (including strawberry, papaya, pineapple, pomegranate, guava, and melon in addition to pre-treatment for sweet potatoes prior to frying), application in Meat and Fish Products (including meat from pork, beef, chicken, and rabbits), applications in Cereal Product (flour dough and bakery products such as bread, crackers, biscuits, wafers, and batters (pancakes, donuts)), application in Dairy Products and Emulsified Products (Chiozzi et al. 2022).

Food processing using non-thermal technologies is well established in scientific literature and subject to increasing research by scientists. Moreover, a broad range of food products already utilize these methods. Continuous synthesis of the literature is needed as it serves to benefit food processors and potentially several others in the supply chain of agro foods. Additionally, it serves to enhance the current knowledge. Therefore, this review aims to offer an appraisal on selective non-thermal food processing technologies with a focus on their operational mechanisms and success in the preservation of numerous types of foods, and to provide an outline on the state-of-the-art applications of non-thermal food processing techniques used in the food industry to improve the mass transfer.

Mass transfer in the food industry

Mass transfer is the movement of a substance between two phases of varying concentrations till a chemical equilibrium is reached (Welti-Chanes et al. 2005). Mass transfer is utilized widely in the food industry across several processes. For example, mass transfer is used in introducing desired substances into food (salting, curing, osmotic dehydration), in extracting desired substances from food (antioxidants, colorants, sugar, fruit juices, etc.) and in removing water from foods (drying) (Chiozzi et al. 2022; Al-Sharify et al. 2020; Welti-Chanes et al. 2005; Onyeaka et al. 2023; Nobel 1999).

Factors influencing the rate of mass transfer vary from the strength of the concentration gradient to the resistance faced by the particles of the substance in transfer between the phases. For food material composed of cells, mass transfer is mainly dependent on diffusion through the cell membrane. Compared to its adjacent aqueous solution, the mean diffusion coefficient of a solute in cell membrane is estimated to be much lesser (Onyeaka et al. 2023). Previously, maintaining food demands quality t typical food preservation techniques subject foods to high temperature, which affects its texture, organoleptic qualities, and temperature-sensitive nutritional components (Jadhav, Annapure, et al. 2021).

Food specialists investigated non-thermal alternatives processing exposes food to ambient temperature for a minute or less, preserving its nutritional value, texture, and mouthfeel. Due to consumer demand for fresh foods with longer shelf life and better taste, non-thermal food treatment has been studied extensively. Non-thermal food processing and preservation processes, which use less power and provide healthier food, may replace thermal methods. Non-thermal methods preserve food better than thermal technologies since they don't produce product qualities or byproducts. When using cold plasma it apparently eliminates microbes at room temperature. As ambient temperature is being used, heat-sensitive foods are protected (Jadhav, Annapure, et al. 2021). Recent studies investigate mass transfer and have examined supercritical fluids employed in supercritical technologies and may substitute organic solvents in many procedures. Supercritical fluids are fluids heated above their critical temperature and pressure. A supercritical fluid is gaseous and liquid-like. Its diffusion coefficient and viscosity are just like gases and liquids. Supercritical fluid, which has enhanced properties like liquid, may be used as a solvent to extract bioactives from various sources, including animals and plants. Fluids change with temperature and pressure. Carbon dioxide is a desirable supercritical fluid in the food processing sector since it may become supercritical at 31.1 °C and 7.4 MPa. Supercritical fluids are used in the food sector for extraction, microbial inactivation, improving mass transfer during synthesis, etc. Among other applications, supercritical extraction is widespread. According to earlier studies, high-pressure carbon dioxide at 1 MPa pressure for 26 h decreased the microbial load of ground beef. A careful review of the literature suggests that supercritical technology might be used in the food processing sector to extract food components and preserve and enhance their physiological qualities for use in functional and nutraceutical formulations (Jadhav, Annapure, et al. 2021). Many authors used thermal processing to enhance food's flavor, texture, applicability, and shelf life. Most food thermal processing methods use heat and mass transfer to achieve these aims and manufacture flavour components from chemical processes. Heat and mass transmission must account for the whole effects of processing on food matrix with intricate physics. Nevertheless, many studies overlook capillarity, shrinkage, and expansion during heat and mass transmission, which leads to model errors. To properly comprehend the relationship between structure and property, including as many of the above factors as possible, especially those that may affect transfer processes, is important. Mass and heat transport frequently cause food deformation during thermal processing. Therefore, mass and heat transfer will be significantly affected. Moreover, shrinkage and processing factors match nicely (temperature, air flow rate, or time) (Li et al. 2022).

In the design of food processing equipment and processes, and the control of food storage and packaging, the mass transfer coefficient of the interface is crucial. The qualities of the food processing equipment used strongly affects transfer coefficients. As such, the mass transfer coefficient is highly significant in the design of drying, separation, and storage processes (Li et al. 2022).

The following correlation can be used to define the surface mass transfer coefficient:

$$J = h_M A (X_A - X_{AS}) \tag{1}$$

where

J = rate of mass transfer (kg/s)h_M = surface mass transfer coefficient at the material-air interface (kg/m^2 s)

A = effective surface area (m^2)

X_{AS} = air humidity at the solid interface (kg/kg)

X_A = air humidity at the bulk air interface (kg/kg)

Calculations using empirical equations with the dimensional numbers below can be performed to determine the mass transfer coefficient. Alternatively, it can be experimentally determined.

$$\text{Mass transfer factor } j_M = \left(\frac{h_M}{\mu\rho}\right) Sc^{2/3} \tag{2}$$

$$\text{Reynolds number } Re = \mu\rho d/\eta \tag{3}$$

$$\text{Schmidt number } Sc = \eta/\rho d \tag{4}$$

where$u$ = air velocity (m/s)ρ = air density (kg/m^3)d = particle diameter (m)η = dynamic viscosity of air (kg/ms)

The Re number depends on the particle diameter d as well as the actual air velocity u. For particles that are non-spherical, d is described as:

$$d = 6V_p/A_p \tag{5}$$

where

V_p = particle volume

A_p = particle surface areak_C, the mass transfer coefficient often utilised in research works is associated to h_M by the following correlation:

$$k_C = h_M/\rho$$

where ρ is the fluid density. At ambient temperature and atmospheric pressure, the dry air density for air/water systems is about 1 kg/m^3. Thus, the magnitude of k_C (m/s) and h_M (kg/m^{2}s) is same (Perry & Green 1997; Saravacos 1997).

Increase in mass transfer is of industrial interest owing to a reduction in operation time. Use of a faster mass transfer velocity in the process produces multiple benefits, such as an increase in productivity, the preservation of physiological and nutritional value of food components, and a reduction in economic costs. Food materials, across many cases, are pre-treated by heat, enzymes, or mechanical grinding to influence and increase the transfer rate. These methods deteriorate the cytoplasmic membrane and increase its permeability, resulting in the loss of the diffusion barrier (Toepfl et al. 2006). However, significant expenditures of thermal and mechanical energies are required for these methods. They can also potentially be destructive to valuable food compounds. Non-thermal food processing techniques can replace these conventional methods in the treatment of food material (Li et al. 2022).

Vegetables and fruits are crucial sources of compounds such as antioxidants, natural colors, fibre, vitamins, and minerals. These nutraceutical compounds are necessities to the human diet and beneficial to the human body (Omolola et al. 2017; Ramya & Jain 2017). Because of their high moisture content, however, biochemical and microbiological changes are common in vegetables and fruits as exhibited by the shortened shelf lives. Dehydration can be used to reduce moisture levels in these foods to low or intermediate levels, and in turn prolong their shelf lives (Chitrakar et al. 2019; Qiu et al. 2019). Using a higher temperature in the dehydration process, reduces the process time but also leads to undesirable changes as in changes to quality parameters, morphometric changes, depletion of thermo-sensitive nutrients, and changes to sensory characteristics (from enzymatic or chemical reactions) (Santillana Farakos et al. 2013). In contrast, osmotic dehydration allows for moisture reduction to intermediate levels whilst improving the taste and appearance of fruits and vegetables by inhibiting enzymatic browning. Osmotic dehydration involves both, the removal of water and the incorporation of solutes (Omolola et al. 2017; Ramya & Jain 2017; Sabarez et al. 2018).

Figure 1 presents a schematic diagram of the osmotic dehydration procedure that usually occurs in vegetables and fruits.

However, mass transfer is slow in osmotic dehydration. Also, there may be loss of food components such as organic acids, minerals, or vitamins (Kuo et al. 2018; Yadav & Singh 2014). Various rate controlling parameters affect the mass transfer rate. Some examples of rate controlling parameters include the process conditions (temperature, agitation, time), the food matrix (physiochemical characteristics), and the osmotic agent in use (concentration and component make up) (Cichowska et al. 2019; Fernandes et al. 2017; González-Pérez et al. 2019; Monnerat et al. 2010; Nowacka, Wiktor, et al. 2019; Nowacka, Laghi, et al. 2019).

Typically, the temperature used in the osmotic dewatering is the parameter altered to reduce the operating times of the process as a rise in the temperature, rises the permeability of the cell membrane, ergo accelerating mass transfer (Akharume et al. 2019; Assis et al. 2016). However, higher process temperatures adversely affect product quality and seen by changes to flavour, texture, color, etc. (Sabarez et al. 2018; Barbosade Lima et al. 2016). Non-thermal methods like osmo-sonification, ultrasound, electrical pulses, vacuum pulses, along with high hydrostatic pressure have been developed to enhance the mass transfer whilst eliminating adverse affects on quality (Dash et al. 2019; de Mello et al. 2019; Martín-Belloso et al. 2018; Nowacka et al. 2018; Osae et al. 2019).

Combining osmotic dehydration with non-thermal methods enables effective reduction of fruit and vegetable processing time. This combined method increases the rate of mass transfer and allows for changes to membrane permeability without affecting product quality (Deng et al. 2019; Dermesonlouoglou et al. 2016; Onwude et al. 2017).

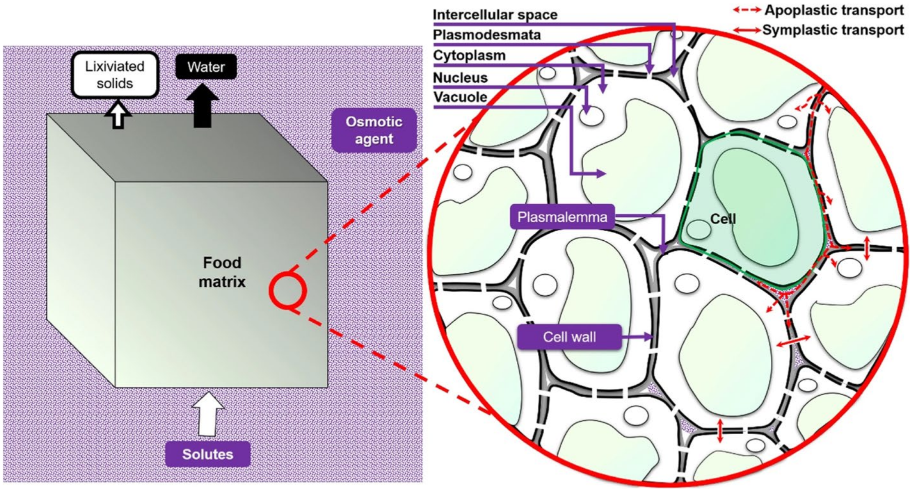


Fig. 1 Mass transfer in osmotic dehydration procedure of vegetables or fruits (González-Pérez et al. 2021)

Pulsed electric field

Pulsed Electric Field (PEF) treatment is the application of low to moderate intensity electric fields by direct current voltage pulses to materials placed in between two electrodes for very brief periods of time. Between the microseconds to milliseconds an electric field is generated due to the voltage pulses, the strength of which is determined by the distance between plates and the voltage applied. Typically, low intensity fields are of strengths < 0.1 kV cm^{-1}, moderate intensity fields are between 0.1 to 1 kV cm^{-1}, and high intensity fields are above 1 kV cm^{-1} although no formal definition exists (Asavasanti et al. 2010).

The mass transfer is improved due to the permeabilization of eukaryote cells. Shorter processing periods vary between 100 to 10,000 µs for electric fields in the range of 1 to 10 kV cm^{-1} (Nowacka et al. 2018). Permeabilization, or cell membrane puncturing enables access through the cell membrane and fluid movement, thereby enhancing mass transfer (Novak & Ribera 2003; Molgaard et al. 2016; Burry 2009).

The limitations of non-thermal processing techniques particularly addressed over the past several decades. Non-thermal techniques classified as value-added technologies have gained prominence as viable alternatives to standard food processing. The direct influence is represented by the reduction of energy effect during storage and the effective reduction of water and energy usage during processing. In contrast, the Influences of non-thermal treatment are projected to lower organic waste and boost the worth of biomass resources (Chemat, Rombaut, Meullemiestre, et al. 2017; Pereira & Vicente 2010). However, food losses, inefficient by-product/processing impurities consumption, and unessential quality degradation within the supply chain are all significant inefficiencies within the food manufacturing industry, the indirect impact of non-thermal processing on food processing sustainability may be even more significant than direct impacts (Pereira & Vicente 2010).

Figure 2 presents the results of one recent experimental investigation that looked at the colour of extraction media after four separate extraction times. Red beetroots were utilised in the study where one sample was untreated (0 kV cm^{-1}) and then samples were treated by pulsed electric fields at varying intensities (1, 3, 5 and 7 kV cm^{-1}). The results revealed that at 7 kV cm^{-1}, the application of five pulses led to an increase of about four times in the overall quantity of betalain obtained through red beetroot (López et al. 2009; Puértolas et al. 2012).

Electroporation, or Electro-permeabilization, is the phenomenon in which applying external electric field pulses for micro-millisecond durations results in

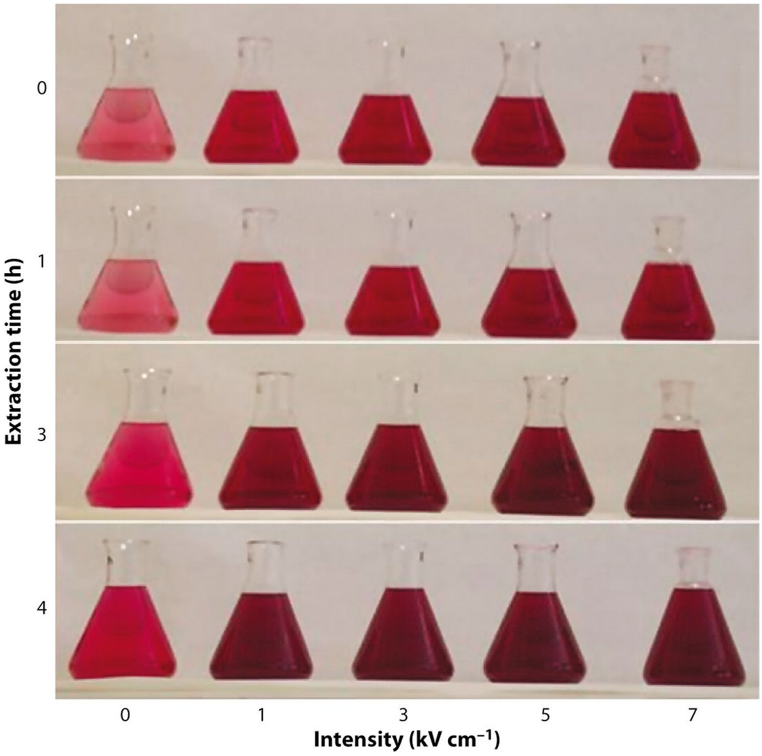


Fig. 2 Effects of different intensities of pulsed electric fields on red beetroots samples (Puértolas et al. 2012)

increases to cell membrane permeability (Tsong 1991). In recent times, electroporation is being suggested as an alternate technique to thermal processing for inactivating microorganisms as it performs effectively with lower temperature requirements. It is also routinely utilized to access and introduce molecules into cell cytoplasm in molecular biology (Teissie et al. 2002).

Electroporation in the food industry for microbial activation and mass transfer increase is irreversible whereas in traditional biotechnical application reversible electroporation is used. Reversible electroporation preserves cell viability by external electric fields application near the critical value. This way the cell membrane is allowed to recover its functionality and structure. Exceeding the critical, as is done in irreversible electroporation, disintegrates the membrane resulting in the loss of cell viability. Experiments on liposomes, which are representative of model systems, and eukaryote cells, individually, have been used to explain electro-permeabilization by some theories. However, cells of food materials make up tissues with inhomogeneous and complex structures having spatially dependent properties. As such, the local electric field distribution represents an intricate function of the electrical characteristics of the material structure, the changes during the PEF treatment, porosity, and constituents (Vorobiev & Lebovka 2006). Whilst a fundamental understanding is crucial in setting the critical process parameters for improves mass transfer with PEF treatment, available information about membrane permeabilization is limited.

From the extraction of sugar and rapeseed oil from sugar beets to the dehydration of red bell peppers and coconuts, the cell disintegration index has proven to be highly beneficial in setting conditions for PEF treatment that are optimized to increase mass transfer (Ade-Omowaye et al. 2000 2003; Eshtiaghi & Knorr 2002; Guderjan et al. 2007). Whilst most studies on PEF treatments have been done at room temperature, PEF-induced damage in plant tissues has been demonstrated to be influenced by temperature. Applying electric fields stronger than the critical value increases cell membrane electroporation. In turn, this increases the mass transfer rate. The transfer rate is dependent of electric field intensity and process times. Increases in field strength beyond the threshold value results in maximum permeabilization and does not increase mass transfer any further (Knorr & Angersbach 1998; Praporscic et al. 2004; Hasan 2022; Mhawesh et al. 2022).

From the above, the capacity for PEF as a viable treatment to improve mass transfer can be seen. Due to advantages such as the short processing times and low energy consumption required for permeabilization of eukaryote cells, PEF treatment should be implemented across the food industrial level immediately. Then to summarize, PEF treatment increases the period for which quality of rehydrated and thawed foods is maintained, decreases the time required for drying and freezing food, and improves the pre-drying diffusion coefficient for water. PEF is used in enhancing the chemical and physical properties of certain polysaccharides and food components (Hasan 2022; Dong et al. 2020; Zhu 2018), the modification of potato starch (Chen et al. 2020), alongside being used in modification of properties of oat flour (Duque et al. 2020). Lastly, because of its high intensity and subsequent enhancement of heat transfer, PEF can be utilised in esterification (Lin et al. 2012) and it increases the rate of reaction and the mass transfer in chelation (Zhang et al. 2017). Advancements in instrumentation dealing with high strength PEF are needed for industrial use due to the numerous benefits of PEF as a non-thermal treatment method (Chemat & Zill-E-Huma 2011).

Ultrasonication

Ultrasonication is a well-established food processing technique across many sectors and is emergent in the food sector. As a non-thermal technology, ultrasonication relies on ultrasound. Ultrasound consists of any sound wave with a frequency higher than 20,000 kHz which is typically the upper limit of normal human hearing (Mason & Cintas 2007). As the ultrasonic waves pass through a medium, they oscillate. The resulting oscillation generates a series of compressions and expansions in the medium. In the presence of air, small cavities are formed. These cavities collapse after reaching a desired size, producing hot spots locally and releasing large amounts of energy. In turn, mass and heat transfer rates are increased (Bhangu & Ashokkumar 2016). Chemical synthesis involving organic compounds is sped up by ultrasonication due to the increased yield produced by the enhanced mass and heat transfer. Shear forces produced in the medium by ultrasonication depends on the frequency as low frequencies produce larger forces and high frequencies produce smaller forces. Matching the frequency to that of the medium, as various sonochemical-assisted processes are optimized, results in the formation of radical species which can lead to oxidative changes to proteins and lipids amongst other undesirable affects (Delmas et al. 2015).

The frequency range utilized in food processes such as in intensified synthesis, debittering, cooking, emulsification, and extraction of bioactives is 20 kHz-100 kHz. On designer lipid synthesis using sonification, Jadhav, Gogate, et al. (2021) reported a 92% maximum yield in 6 h of the reaction. Ultrasonication as an alternative to intensify yield is excellent as it increases the rate of mass transfer. Compared to conventional synthesis, ultrasonication-assisted synthesis is rapid and benefits from high-energy spot generation (Jadhav & Annapure 2021). Ultrasound, by assisting the interfacial transfer of molecules, enhances the extraction of bioactives whilst improving the chemical and physical properties of the extracted bioactives from animal and plant sources. This was reported recently by Sun et al. (2020), who found superior properties for protein extracted from ultrasonication in terms of structure, emulsification power and size of particle.

Ultrasonic-assisted filtration is utilized within the dairy and beverage industry. For example, due to its effectiveness, the process of membrane filtration is utilised in the cheese making industry to completely separate milk protein from other milk solids (Saxena et al. 2009). For procedures involving drying, thawing as well as freezing of food products, ultrasonication is also highly useful (Chow et al. 2005; Miles et al. 1999; Cheng et al. 2014). After reviewing ultrasound technology for food fermentation application, Ojha et al. (2017) showed that a better process and production rate could be obtained using a low frequency between 20–50 kHz due to enhancements to both mass transfer and cell permeability (Prestes et al. 2023).

Ultrasound has proven its viability as a potential alternative across critical areas of the food sector. These areas include food preservation, extraction, and intensified synthesis alongside the advancement of chemical and physical characteristics of foods. Due to a lack of consumer awareness and limited technical information, ultrasonication has faced poor commercialization prospects within the food industry. As such, an understanding of the effects of ultrasonication of bulk food is important before industrial wide implementation (Jadhav, Annapure, et al. 2021; Prestes et al. 2023).

Supercritical technology

Supercritical technology is based on the use of supercritical fluids. These are fluids that attain a supercritical state due to heating beyond the critical temperature and pressure and show a mix of properties of liquids and gases. These fluids show viscosity and diffusivity like gasses and density like liquids (Mason & Cintas 2007). They are considered good organic solvent replacements in various processes as such (Temelli et al. 2012). For example, in bioactives extraction from animal and plant sources, supercritical fluids can be used as solvents to increase mass transfer rate. Another added benefit is that their properties can be tuned by varying the temperatures as well as pressures. Amongst several other fluids, carbon dioxide as a supercritical fluid is excellent for use in the food processing industry due to its modest pressure and temperature requirements (7.4 MPa and 31.1 °C, respectively) to attain its supercritical state. Whilst primarily employed in extraction processes, supercritical fluids have also found use in synthesis mass transfer enhancement, microbial inactivation, etc.

For the purpose of extraction, supercritical carbon dioxide is used as it easily separated from the final product and is non-toxic (Brunner 2005; Deotale et al. 2021). The quality of material extracted is much higher as natural bioactives are susceptible to effects of temperature and oxygen. Using supercritical carbon dioxide, allows the use of low temperatures and ensures there is no contamination by oxygen. The extracted material can be used in various nutraceutical formulations as a functional ingredient (Deotale et al. 2021).

Utilising supercritical carbon dioxide in extraction for many purposes and has been popular in the food processing industry for several years (Pinto et al. 2020; Gallego et al. 2019; Torres-Ossandón et al. 2018; Priyanka 2020; Ferrentino et al. 2020; Rebolleda et al. 2012; De Oliveira et al. 2014; Salea et al. 2017; Al-Otoom et al. 2014; Molino et al. 2020; Pavlić et al. 2020; Santos et al. 2020; Priyanka 2018; Fornari et al. 2012; Spilimbergo & Bertucco 2003; Koubaa et al. 2018; Silva et al. 2020; Rushdi et al. 2020; Onyeaka, Miri, et al. 2021; Agbugba et al. 2022; Obileke et al. 2022; Onyeaka et al. 2022; Zaid et al. 2022). It is used in the extraction of bioactives, usable as components in nutraceutical formulations, such as quercetin, anthocyanins, astaxanthin, lycopene, and carotenoids (Pinto et al. 2020; Gallego et al. 2019; Torres-Ossandón et al. 2018), extraction of essential oils (Priyanka 2020; Ferrentino et al. 2020), extraction of green coffee oil and corn germ oil (Rebolleda et al. 2012; De Oliveira et al. 2014), oil from ginger (Salea et al. 2017), oil from olives (Al-Otoom et al. 2014), extraction of fruit seed oil (Molino et al. 2020; Pavlić et al. 2020; Santos et al. 2020; Priyanka 2018; Fornari et al. 2012) and nutraceutical and functional ingredient extraction from microalgae (Molino et al. 2020). Moreover, supercritical technology can be used in microbial load reduction in food. By reducing the pH of bacterial cells, supercritical fluid treatment leads to cell rupture and subsequent bacterial enzyme inactivation. These enzymes are responsible for anabolism and catabolism. As a result, the bacterial cells perish, and the microbial load is reduced (Spilimbergo & Bertucco 2003). The original and organoleptic characteristics of food are retained (Koubaa et al. 2018) whilst using supercritical technology treatment as the operating temperature is low. For example, it is widely used in the preservation of fruits and vegetables and their juices (Silva et al. 2020). Lastly, supercritical fluids are also used for ground meat preservation. More recent studies on food processing using supercritical technology increased dramatically with the wide spread of COVID-19 virus worldwide (Aditya & Kim 2022; Al-Mashhadani et al. 2020; Ekwebelem et al. 2021; Greene et al. 2022; Hamad et al. 2020; Onyeaka, Al-Sharify, et al. 2021; Onyeaka, Anumudu, et al. 2021; Rushdi et al. 2020; Shakor 2022; Sun et al. 2022; Uwishema, Adekunbi, et al. 2022; Uwishema et al. 2021; Uwishema, Chalhoub, et al. 2022; Uwishema, Chalhoub, Zahabioun, et al. 2022; Uwishema, Taylor, et al. 2022; Al-Sharify et al. 2022; Braga et al. 2023), including the use of three-dimension printing of meat following supercritical fluid extraction controlled remotely through the use of IoT system (Aditya & Kim 2022). Recent study focused on supercritical fluid, non-thermal processing, and food science innovations. eliminating germs and mycotoxins in fruit juices while keeping taste and nutrition with healthier options using s upercritical Technology handling Cereal Byproducts. The potential of supercritical technology to valorize maize milling byproducts by evaluating trademarks, techniques, economic feasibility, and future usage (Braga et al. 2023; Barros et al. 2023; Lopes et al. 2023; Santana & Meireles 2023). Reviewing the literature on supercritical technology critically showed the bright potential for supercritical technology in food processing with its usefulness in the enhancement and preservation of physical qualities of food constituents for use as practical ingredients in nutraceutical and functional formulas, alongside its extensive use in extraction (Santana & Meireles 2023).

Conclusions

Non-thermal food processing treatments are being employed more frequently in the food industry because of its advantages with regards to shorter exposure time and lower temperature of treatment which preserves food quality while eliminating possible pathogenic and spoilage organisms in food. Furthermore, there are practically minimal or no chances of heat damage to the food product, ensuring the maintenance of the nutritional and organoleptic quality of the food. This review studied certain selected non-thermal food processing technologies by paying focus on their operational mechanisms and success in the preservation of different types of foods. Also, the review provides an outline on the state-of-the-art uses of non-thermal food processing techniques used in the food industry to improve mass transfer. Increase in mass transfer is of industrial interest owing to a reduction in operation time. Use of a faster mass transfer velocity in the process produces multiple benefits, such as an increase in productivity, the preservation of physiological and nutritional value of food components, and a reduction in economic costs. The review demonstrates that techniques such as Pulsed Electric Field, Ultrasonication and Supercritical technology are viable treatments for enhancing mass transfers in food processing. Due to limitations in understanding the effects of these different non-thermal treatments, it is recommended that further research work is carried out on these techniques before their industrial wide implementation takes place.

Acknowledgements

The authors would like to thank Al-Nahrain University -Iraq and Mustansiriyah University (www.uomustansiriyah.edu.iq) Baghdad-Iraq for its support in the current work. The authors also would like to acknowledge the support of the Birmingham University - UK, for their valuable support.

Authors' contributions

All authors were involved in the preparation and writing of the manuscript. Conceptualization: HO, ZTA and SZA, Initial draft: HO, TM, KO and CKA, Revising and review: ZTA, TM, KO and SZA, References: CKA. The author(s) read and approved the final manuscript.

Funding

This work did not receive any funding.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not Applicable as no animals or organisms were involved in this study. Thus, no ethical clearance or statement is required.

Consent for publication

Not Applicable.

Competing interests

Authors declare no competing interest.

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Received: 23 January 2023 Accepted: 16 April 2023

References

Ade-Omowaye, B. I. O., Angersbach, A., Eshtiaghi, N. M., & Knorr, D. (2000). Impact of high intensity electric field pulses on cell permeabilisation and as pre-processing step in coconut processing. *Innovative Food Science and Emerging Technologies*, *1*, 203–209.

Ade-Omowaye, B. I. O., Taiwo, K. A., Eshtiaghi, N. M., Angersbach, A., & Knorr, D. (2003). Comparative evaluation of the effects of pulsed electric field and freezing on cell membrane permeabilisation and mass transfer during dehydration of red bell peppers. *Innovative Food Science and Emerging Technologies*, *4*, 177–188.

Aditya, A. A., & Kim, N. P. (2022). 3D printing of meat following supercritical fluid extraction. *Foods*, *11*(4), 554. https://doi.org/10.3390/foods11040554.

Agbugba, I. K., Agbagwa, S. K., Anumudu, C. K., Ekwebelem, O. C., Al-Sharify, Z. T., Isaac-Bamgboye, F. J., & Onyeaka, H. (2022). The evolving state of food security in Nigeria amidst the COVID-19 pandemic – A review. *Open Agriculture*, *7*(1), 899–909. https://doi.org/10.1515/opag-2022-0149.

Akharume, F., Smith, A., Sivanandan, L., & Singh, K. (2019). Recent progress on osmo-convective dehydration of fruits. *SDRP Journal of Food Science & Technology*, *4*(9), 956–969. https://doi.org/10.25177/JFST.4.9.RA.613.

Al-Mashhadani, S. H., Al-Sharify, Z. T., & Kariem, N. O. (2020). Investigating the spread of coronavirus (Covid-19) at airports and methods of protection. *Journal of Engineering and Sustainable Development*, (Special), 38–44. https://doi.org/10.31272/jeasd.conf.1.4.

Al-Otoom, A., Al-Asheh, S., Allawzi, M., Mahshi, K., Alzenati, N., & Banat, B. (2014). Extraction of oil from uncrushed olives using supercritical fluid extraction method. *Journal of Supercritical Fluids*, *95*, 512–518. https://doi.org/10.1016/j.supflu.2014.10.023.

Al-Sharify, Z. T., Al-Sharify, T. A., Al-Obaidy, B. W., & Al-Azawi, A. M. (2020). Investigative study on the interaction and applications of plasma activated water (PAW). *IOP Conference Series: Materials Science and Engineering*, *870*(1), 012042. https://doi.org/10.1088/1757-899X/870/1/012042.

Al-Sharify, T. A., Alshrefy, Z. A., Hussein, H. A., Al-Sharify, Z. T., Onyeaka, H., Al-Sharify, M. T., & Ghosh, S. (2022). IoT and E-learning with the impact of COVID 19 pandemic lockdown on the undergraduate university student blood pressure levels. *CEUR Workshop Proceedings*, *3149*, 73–86.

Asavasanti, S., Ersus, S., Ristenpart, W., Strove, P., & Barret, D. M. (2010). Critical field strength of onions tissues treated by pulsed electric fields. *Journal of Food Science*, *75*, 433–443. https://doi.org/10.1111/j.1750-3841.2010.01768.x. PMID: 21535537.

Assis, F. R., Morais, R. M. S. C., & Morais, A. M. M. B. (2016). Mass transfer in osmotic dehydration of food products: Comparison between mathematical models. *Food Engineering Reviews*, *8*(2), 116–133. https://doi.org/10.1007/s12393-015-9123-1.

Bahrami, A., Baboli, Z. M., Schimmel, K., Jafari, S. M., & Williams, L. (2020). Efficiency of novel processing technologies for the control of Listeria monocytogenes in food products. *Trends in Food Science & Technology*, *96*, 61–78.

Barbosade Lima, A. G., da Silva, J. V., Pereira, E. M. A., dos Santos, I. B., & de Lima, W. M. P. B. (2016). Drying of bioproducts: quality and energy aspects. In J. M. P. Q. Delgado & A. G. Barbosa (Eds.), *Drying and Energy Technol* (Vol. 63, pp. 1–18). Springer International Publishing. https://doi.org/10.1007/978-3-319-19767-8_1.

Barros, C. P., Guimarães, J. T., Pimentel, T. C., Esmerino, E. A., Villanueva-Rodríguez, S. J., & da Cruz, A. G. (2023). Supercritical fluid. *Novel Technologies in Food Science*, 405–449. https://doi.org/10.1002/9781119776376.ch11.

Bellisle, F. (1998). *Functional food science in Europe*. Published on behalf of the Nutrition Society by CABI Pub.

Bhangu, S. K., & Ashokkumar, M. (2016). Theory of sonochemistry. *Topics in Current Chemistry*, *374*, 1–28. https://doi.org/10.1007/978-3-319-54271-3_1.

Bhattacharjee, C., Saxena, V., & Dutta, S. (2019). Novel thermal and non-thermal processing of watermelon juice. *Trends in Food Science & Technology*, *93*, 234–243.

Braga, M. E., Gaspar, M. C., & de Sousa, H. C. (2023). Supercritical fluid technology for agrifood materials processing. *Current Opinion in Food Science*, 100983. https://doi.org/10.1016/j.cofs.2022.100983..

Brunner, G. (2005). Supercritical fluids: Technology and application to food processing. *Journal of Food Engineering*, *67*, 21–33. https://doi.org/10.1016/j.jfoodeng.2004.05.060.

Burry, R. W. (2010). *Immunocytochemistry*. Springer Science+ Business Media. 10, 978-1. https://doi.org/10.1007/978-1-4419-1304-3.

Chacha, J. S., Zhang, L., Ofoedu, C. E., Suleiman, R. A., Dotto, J. M., Roobab, U., Agunbiade, A. O., Duguma, H. T., Mkojera, B. T., Hossaini, S. M., Rasaq, W. A., Shorstkii, I., Okpala, C., Korzeniowska, M., & Guiné, R. (2021). Revisiting non-thermal food processing and preservation methods-action mechanisms, pros and cons: A technological update (2016–2021). *Foods (Basel, Switzerland)*, *10*(6), 1430. https://doi.org/10.3390/foods10061430.

Chemat, F., & Zill-E-Huma, K. M. K. (2011). Applications of ultrasound in food technology: Processing, preservation and extraction. *Ultrasonics Sonochemistry*, *18*, 813–835. https://doi.org/10.1016/j.ultsonch.2010.11.023.

Chemat, F., Rombaut, N., Sicaire, A.-G., Meullemiestre, A., Fabiano-Tixier, A.-S., & Abert-Vian, M. (2017). Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A Review. *Ultrasonics Sonochemistry*, *34*, 540–560.

Chemat, F., Rombaut, N., Meullemiestre, A., Turk, M., Perino, S., & Fabiano-Tixier, A.-S. (2017). Review of green food processing techniques. Preservation, transformation, and extraction. *Innovative Food Science and Emerging Technologies*, *41*, 357–377. https://doi.org/10.1016/j.ifset.2017.04.016.

Chen, B. R., Wen, Q. H., Zeng, X. A., Abdul, R., Roobab, U., & Xu, F. Y. (2020). Pulsed electric field assisted modification of octenyl succinylated potato starch and its influence on pasting properties. *Carbohydrate Polymers*, *254*, 117294. https://doi.org/10.1016/j.carbpol.2020.117294.

Cheng, X. F., Zhang, M., & Adhikari, B. (2014). Effect of ultrasonically induced nucleation on the drying kinetics and physical properties of freeze-dried strawberry. *Drying Technology*, *32*, 1857–1864. https://doi.org/10.1080/07373937.2014.952741.

Chiozzi, V., Agriopoulou, S., & Varzakas, T. (2022). Advances, applications, and comparison of thermal (pasteurization, sterilization, and aseptic packaging) against non-thermal (ultrasounds, UV radiation, ozonation, high hydrostatic pressure) technologies in food processing. *Applied Sciences*, *12*(4), 2202. https://doi.org/10.3390/app12042202.

Chitrakar, B., Zhang, M., & Adhikari, B. (2019). Dehydrated foods: Are they microbiologically safe? *Critical Reviews in Food Science and Nutrition*, *59*(17), 2734–2745. https://doi.org/10.1080/10408398.2018.1466265.

Chow, R., Blindt, R., Chivers, R., & Povey, M. (2005). A study on the primary and secondary nucleation of ice by power ultrasound. *Ultrasonics*, *43*, 227–230. https://doi.org/10.1016/j.ultras.2004.06.006.

Cichowska, J., Figiel, A., Stasiak-Różańska, L., & Witrowa-Rajchert, D. (2019). Modeling of osmotic dehydration of apples in sugar alcohols and dihydroxyacetone (DHA) solutions. *Foods*, *8*(1), 20. https://doi.org/10.3390/foods8010020.

Dash, K. K., Balasubramaniam, V. M., & Kamat, S. (2019). High pressure assisted osmotic dehydrated ginger slices. *Journal of Food Engineering*, *247*, 19–29. https://www.sciencedirect.com/science/article/pii/S0260877418305065?via%3Dihub#:~:text=https%3A//doi.org/10.1016/j.jfoodeng.2018.11.024.

de Mello, R. E., Jr., Corrêa, J. L. G., Lopes, F. J., de Souza, A. U., & da Silva, K. C. R. (2019). Kinetics of the pulsed vacuum osmotic dehydration of green fig (Ficus carica L.). *Heat and Mass Transfer*, *55*(6), 1685–1691. https://doi.org/10.1007/s00231-018-02559-w.

De Oliveira, P. M. A., De Almeida, R. H., De Oliveira, N. A., Bostyn, S., Gonçalves, C. B., & De Oliveira, A. L. (2014). Enrichment of diterpenes in green coffee oil using supercritical fluid extraction - characterization and comparison with green coffee oil from pressing. *The Journal of Supercritical Fluids*, *95*, 137. https://doi.org/10.1016/j.supflu.2014.08.016.

Delmas, H., & Barthe, L. (2015). Ultrasonic mixing, homogenization, and emulsification in food processing and other applications. In J. Gallego, F. Karl, & A. Juan (Eds.), *Power ultrasonics: Applications of high-intensity ultrasound* (pp. 757–91). Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-028-6.00025-9.

Deng, L.-Z., Mujumdar, A. S., Zhang, Q., Yang, X.-H., Wang, J., Zheng, Z.-A., Gao, Z.-J., & Xiao, H.-W. (2019). Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes – A comprehensive review. *Critical Reviews in Food Science and Nutrition*, *59*(9), 1408–1432. https://doi.org/10.1080/10408398.2017.1409192.

Deotale, S. M., Dutta, S., Moses, J. A., & Anandharamakrishnan, C. (2021). Advances in supercritical carbon dioxide assisted sterilization of biological matrices. In K. Knoerzer, P. Juliano, & G. Smithers (Eds.), *Innovative food processing technologies* (pp. 660–77). Wiley. https://doi.org/10.1016/B978-0-08-100596-5.22932-6.

Dermesonlouoglou, E., Zachariou, I., Andreou, V., & Taoukis, P. S. (2016). Effect of pulsed electric fields on mass transfer and quality of osmotically dehydrated kiwifruit. *Food and Bioproducts Processing*, *100*, 535–544. https://doi.org/10.1016/j.fbp.2016.08.009.

Dong, M., Xu, Y., Zhang, Y., Han, M., Wang, P., & Xu, X. (2020). Physicochemical and structural properties of myofibrillar proteins isolated from pale, soft, exudative (PSE)-like chicken breast meat: effects of pulsed electric field (PEF). *Innovative Food Science & Emerging Technologies*, *59*, 102277. https://doi.org/10.1016/j.ifset.2019.102277.

Dong, X., Wang, J., & Raghavan, V. (2021). Critical reviews and recent advances of novel non-thermal processing techniques on the modification of food allergens. *Critical Reviews in Food Science and Nutrition*, *61*, 196–210.

Duque, S. M. M., Leong, S. Y., Agyei, D., Singh, J., Larsen, N., & Oey, I. (2020). Understanding the impact of Pulsed Electric Fields treatment on the thermal and pasting properties of raw and thermally processed oat flours. *Food Research International*, *129*, 108839. https://doi.org/10.1016/j.foodres.2019.108839.

Ekwebelem, O. C., Yunusa, I., Onyeaka, H., Ekwebelem, N. C., & Nnorom-Dike, O. (2021). COVID-19 vaccine rollout: Will it affect the rates of vaccine hesitancy in Africa? *Public Health*, *197*, e18–e19. https://doi.org/10.1016/j.puhe.2021.01.010.

Eshtiaghi, M. N., & Knorr, D. (2002). High electric field pulse pretreatment: Potential for sugar beet processing. *Journal of Food Engineering*, *52*, 265–272.

Fernandes, F. A. N., & Rodrigues, S. (2017). Osmotic dehydration and blanching: ultrasonic pre-treatments. In M. Villamiel, A. Montilla, J. V. García-Pérez, J. A. Cárcel, & J. Benedito (Eds.), *Ultrasound Food Proc* (pp. 311–328). Wiley. https://doi.org/10.1002/9781118964156.ch11.

Ferrentino, G., Giampiccolo, S., Morozova, K., Haman, N., Spilimbergo, S., & Scampicchio, M. (2020). Supercritical fluid extraction of oils from apple seeds: process optimization, chemical characterization and comparison with a conventional solvent extraction. *Innovative Food Science & Emerging Technologies*, *64*, 102428. https://doi.org/10.1016/j.ifset.2020.102428.

Fornari, T., Vicente, G., Vázquez, E., García-Risco, M. R., & Reglero, G. (2012). Isolation of essential oil from different plants and herbs by supercritical fluid extraction. *Journal of Chromatography A*, *1250*, 34–48. https://doi.org/10.1016/j.chroma.2012.04.051.

Gallego, R., Bueno, M., & Herrero, M. (2019). Sub- and supercritical fluid extraction of bioactive compounds from plants, food-by-products, seaweeds and microalgae – an update. *TrAC Trends in Analytical Chemistry*, *116*, 198–213. https://doi.org/10.1016/j.trac.2019.04.030.

González-Pérez, J. E., López-Méndez, E. M., Luna-Guevara, J. J., Ruiz-Espinosa, H., Ochoa-Velasco, C. E., & Ruiz-López, I. I. (2019). Analysis of mass transfer and morphometric characteristics of white mushroom (Agaricus bisporus) pilei during osmotic dehydration. *Journal of Food Engineering*, *240*, 120–132. https://doi.org/10.1016/j.jfoodeng.2018.07.026.

González-Pérez, J., Ramírez-Corona, N., & López-Malo, A. (2021). Mass Transfer during osmotic dehydration of fruits and vegetables: Process factors and non-thermal methods. *Food Engineering Reviews*, *13*(2), 344–374. https://doi.org/10.1007/s12393-020-09276-3.

Gould, G. (2011). *New methods of food preservation*. Springer.

Greene, L., Uwishema, O., Nicholas, A., Kapoor, A., Berjaoui, C., Adamolekun, E., Khoury, C., Mohammed, F. E. A., & Onyeaka, H. (2022). Crimean-Congo haemorrhagic fever during the COVID-19 pandemic in Africa: Efforts, recommendations and challenges at hand. *African Journal of Emergency Medicine*, *12*(2), 117–120. https://doi.org/10.1016/j.afjem.2022.02.004.

Guderjan, M., Elez-Martinez, P., & Knorr, D. (2007). Application of pulsed electric fields at oil yield and content of functional food ingredients at the production of rapeseed oil. *Innovative Food Science and Emerging Technologies*, *8*, 55–62.

Guzel-Seydim, Z. B., Greene, A. K., & Seydim, A. C. (2004). Use of ozone in the food industry. *LWT*, *37*, 453–460.

Hamad, H. T., Al-Sharify, Z. T., Al-Najjar, S. Z., & Gadooa, Z. A. (2020). A review on nanotechnology and its applications on fluid flow in agriculture and water recourses. *IOP Conference Series: Materials Science and Engineering*, *870*(1), 012038. https://doi.org/10.1088/1757-899X/870/1/012038.

Hasan, B. O. (2022). Single bubble breakage in oil under stirring conditions. *Al-Nahrain Journal for Engineering Sciences*, *25*(1), 6–11. https://doi.org/10.29194/NJES.25010006.

Hendrickx, M., & Knorr, D. (2002). *Ultra high pressure treatment of foods*. Kluwer Academic.

Hernández-Hernández, H., Moreno-Vilet, L., & Villanueva-Rodríguez, S. (2019). Current status of emerging food processing technologies in Latin America: Novel non-thermal processing. *Innovative Food Science and Emerging Technologies*, *58*, 102233.

Jadhav, H. B., & Annapure, U. (2021). Process intensification for synthesis of triglycerides of capric acid using green approaches. *Journal of the Indian Chemical Society*, *98*, 100030. https://doi.org/10.1016/j.jics.2021.100030.

Jadhav, H. B., Gogate, P. R., Waghmare, J. T., & Annapure, U. S. (2021). Intensified synthesis of palm olein designer lipids using sonication. *Ultrasonics Sonochemistry*, *73*, 105478. https://doi.org/10.1016/j.ultsonch.2021.105478.

Jadhav, H., Annapure, U., & Deshmukh, R. (2021). Non-thermal technologies for food processing. *Frontiers in Nutrition*, *8*, 657090. https://doi.org/10.3389/fnut.2021.657090.

Knockaert, G., Pulissery, S. K., Lemmens, L., Van Buggenhout, S., Hendrickx, M., & Van Loey, A. (2012). Carrot β-carotene degradation and isomerization kinetics during thermal processing in the presence of oil. *Journal of Agriculture and Food Chemistry*, *60*, 10312–10319.

Knorr, D. (1983). *Sustainable food systems*. AVI Publishing Company.

Knorr, D. (2003). Impact of non-thermal processing on plant metabolites. *Journal of Food Engineering*, *56*(2–3), 131–134.

Knorr, D., & Angersbach, A. (1998). Impact of high-intensity electric field pulses on plant membrane permeabilization. *Trends in Food Science & Technology*, *9*, 185–191.

Komanapalli, I. R., & Lau, B. H. S. (1996). Ozone-induced damage of Escherichia coli K-12. *Applied Microbiology and Biotechnology*, *46*, 610–614.

Koubaa, M., Mhemdi, H., & Fages, J. (2018). Recovery of valuable components and inactivating microorganisms in the agro-food industry with ultrasound assisted supercritical fluid technology. *Journal of Supercritical Fluids*, *134*, 71–79. https://doi.org/10.1016/j.supflu.2017.12.012.

Kuo, C.-H., Lin, J., Huang, C.-Y., Hsieh, S.-L., Li, S., Kuo, J.-M., & Shieh, C.-J. (2018). Predicting sugar content of candied watermelon rind during osmotic dehydration. *Food Science and Technology*, *38*(suppl 1), 228–235. https://doi.org/10.1590/fst.18817.

La Peña, M.M.-D., Welti-Chanes, J., & Martín-Belloso, O. (2019). Novel technologies to improve food safety and quality. *Current Opinion in Food Science*, *30*, 1–7.

Li, J., Deng, Y., Xu, W., Zhao, R., Chen, T., Wang, M., Xu, E., Zhou, J., Wang, W., & Liu, D. (2022). Multiscale modeling of food thermal processing for insight, comprehension, and utilization of heat and mass transfer: A state-of-the-art review. *Trends in Food Science & Technology*, *131*, 31–45. https://doi.org/10.1016/j.tifs.2022.11.018.

Lin, Z. R., Zeng, X. A., Yu, S. J., & Sun, D. W. (2012). Enhancement of ethanol-acetic acid esterification under room temperature and non-catalytic condition via pulsed electric field application. *Food and Bioprocess Technology*, *5*, 2637–2645. https://doi.org/10.1007/s11947-011-0678-4.

Lopes, S. J., de Souza Sant'Ana, A., & Freire, L. (2023). Non-thermal emerging processing Technologies: Mitigation of microorganisms and mycotoxins and sensory and nutritional properties maintenance in clean label fruit juices. *Food Research International*, 112727. https://doi.org/10.1016/j.foodres.2023.112727.

Lopez, N., Puertolas, E., Condon, S., Raso, J., & Alvarez, I. (2009). Enhancement of the extraction of betanine from red beetroot by pulsed electric fields. *Journal of Food Engineering*, *90*, 60–66.

Martín-Belloso, O., & Morales-de la Peña, M. (2018). Fruit preservation by ohmic heating and pulsed electric fields. In A. Rosenthal, R. Deliza, J. Welti-Chanes, & G. V. Barbosa-Cánovas (Eds.), *Fruit preserv* (pp. 441–456). Springer. https://doi.org/10.1007/978-1-4939-3311-2_16.

Mason, T. J., & Cintas, P. (2007). Sonochemistry. *Handbook of Green Chemistry and Technology*, *2021*, 372–96. https://doi.org/10.1002/9780470988305.ch16.

Mhawesh, A. M., Hasan, B. O., & Znad, H. (2022). Hydrodynamics of stirred tank and bubble breakup behavior induced by rushton turbine. *Al-Nahrain Journal for Engineering Sciences*, *25*(1), 35–43. https://doi.org/10.29194/NJES.25010035.

Miles, C. A., Morley, M. J., & Rendell, M. (1999). High power ultrasonic thawing of frozen foods. *Journal of Food Engineering*, *39*, 151–159. https://doi.org/10.1016/S0260-8774(98)00155-1.

Molgaard, S., Ulrichsen, M., Olsen, D., & Glerup, S. (2016). Detection of phosphorylated Akt and MAPK in cell culture assays. *MethodsX*, *3*, 386–398.

Molino, A., Mehariya, S., Di Sanzo, G., Larocca, V., Martino, M., & Leone, G. P. (2020). Recent developments in supercritical fluid extraction of bioactive compounds from microalgae: Role of key parameters, technological achievements and challenges. *Journal of CO2 Utilization*, *36*, 196–209. https://doi.org/10.1016/j.jcou.2019.11.014.

Monnerat, S. M., Pizzi, T. R. M., Mauro, M. A., & Menegalli, F. C. (2010). Osmotic dehydration of apples in sugar/salt solutions: Concentration profiles and effective diffusion coefficients. *Journal of Food Engineering*, *100*(4), 604–612. https://doi.org/10.1016/j.jfoodeng.2010.05.008.

Nobel, P. S. (1999). *Physicochemical and environmental plant physiology* (2nd ed., p. 461). Academic.

Novak, A. E., & Ribera, A. B. (2003). Immunocytochemistry as a tool for zebrafish developmental neurobiology. *Methods in Cell Science*, *25*, 79–83.

Nowacka, M., Tylewicz, U., Tappi, S., Siroli, L., Lanciotti, R., Romani, S., & Witrowa-Rajchert, D. (2018). Ultrasound assisted osmotic dehydration of organic cranberries (Vaccinium oxycoccus): Study on quality parameters evolution during storage. *Food Control*, *93*, 40–47. https://doi.org/10.1016/j.foodcont.2018.05.005.

Nowacka, M., Wiktor, A., Anuszewska, A., Dadan, M., Rybak, K., & Witrowa-Rajchert, D. (2019). The application of unconventional technologies as pulsed electric field, ultrasound and microwave-vacuum drying in the production of dried cranberry snacks. *Ultrasonics Sonochemistry*, *56*, 1–13. https://doi.org/10.1016/j.ultsonch.2019.03.023.

Nowacka, M., Laghi, L., Rybak, K., Dalla Rosa, M., Witrowa-Rajchert, D., & Tylewicz, U. (2019). Water state and sugars in cranberry fruits subjected to combined treatments: Cutting, blanching and sonication. *Food Chemistry*, *299*, 125122. https://doi.org/10.1016/j.foodchem.2019.125122.

O'Donnell, C. P., Tiwari, B. K., Cullen, P. J., & Rice, R. G. (2012). *Ozone in food processing* (p. 308). Wiley. ISBN 978-1-4443-3442-5.

Obileke, K., Onyeaka, H., Miri, T., Nwabor, O. F., Hart, A., Al-Sharify, Z. T., Al-Najjar, S., & Anumudu, C. (2022). Recent advances in radio frequency, pulsed light, and cold plasma technologies for food safety. *Journal of Food Process Engineering*, *45*(10), e14138. https://doi.org/10.1111/jfpe.14138.

Ojha, K. S., Mason, T. J., O'Donnell, C. P., Kerry, J. P., & Tiwari, B. K. (2017). Ultrasound technology for food fermentation applications. *Ultrasonics Sonochemistry*, *34*, 410–417.

Omolola, A. O., Jideani, A. I. O., & Kapila, P. F. (2017). Quality properties of fruits as affected by drying operation. *Critical Reviews in Food Science and Nutrition*, *57*(1), 95–108. https://doi.org/10.1080/10408398.2013.859563.

Onwude, D. I., Hashim, N., Janius, R., Abdan, K., Chen, G., & Oladejo, A. O. (2017). Non-thermal hybrid drying of fruits and vegetables: A review of current technologies. *Innovative Food Science and Emerging Technologies*, *43*, 223–238. https://doi.org/10.1016/j.ifset.2017.08.010.

Onyeaka, H., Miri, T., Obileke, K., Hart, A., Anumudu, C., & Al-Sharify, Z. T. (2021). Minimizing carbon footprint via microalgae as a biological capture. *Carbon Capture Science & Technology*, *1*, 100007. https://doi.org/10.1016/j.ccst.2021.100007.

Onyeaka, H., Al-Sharify, Z. T., Ghadhban, M. Y., & Al-Najjar, S. Z. (2021). A review on the advancements in the development of vaccines to combat coronavirus disease 2019. *Clinical and Experimental Vaccine Research*, *10*(1), 6–12. https://doi.org/10.7774/cevr.2021.10.1.6.

Onyeaka, H., Anumudu, C. K., Al-Sharify, Z. T., Egele-Godswill, E., & Mbaegbu, P. (2021). COVID-19 pandemic: A review of the global lockdown and its far-reaching effects. *Science Progress*, *104*(2), 368504211019854. https://doi.org/10.1177/00368504211019854.

Onyeaka, H., Passaretti, P., Miri, T., & Al-Sharify, Z. T. (2022). The safety of nanomaterials in food production and packaging. *Current Research in Food Science*, *5*, 763–774. https://doi.org/10.1016/j.crfs.2022.04.005. ISSN 2665-9271.

Onyeaka, H., Nwaiwu, O., Obileke, K., Miri, T., & Al-Sharify, Z. T. (2023). Global nutritional challenges of reformulated food: A review. *Food Science and Nutrition*, *00*, 1–17. https://doi.org/10.1002/fsn3.3286.

Osae, R., Zhou, C., Xu, B., Tchabo, W., Tahir, H. E., Mustapha, A. T., & Ma, H. (2019). Effects of ultrasound, osmotic dehydration, and osmosonication pretreatments on bioactive compounds, chemical characterization, enzyme inactivation, color, and antioxidant activity of dried ginger slices. *Journal of Food Biochemistry*, *43*(5), 1–14. https://doi.org/10.1111/jfbc.12832.

Pavlić, B., Pezo, L., Marić, B., Tukuljac, L. P., Zeković, Z., & Solarov, M. B. (2020). Supercritical fluid extraction of raspberry seed oil: experiments and modelling. *The Journal of Supercritical Fluids*, *157*, 104687. https://doi.org/10.1016/j.supflu.2019.104687.

Pereira, R. N., & Vicente, A. A. (2010). Environmental impact of novel thermal and non-thermal technologies in food processing. *Food Research International*, *43*, 1936–1943. https://doi.org/10.1016/j.foodres.2009.09.013.

Perry, J. H., & Green, D. (1997). *Chemical engineer's handbook* (7th ed.). McGraw-Hill.

Pinto, D., De La Luz Cádiz-Gurrea, M., Sut, S., Ferreira, A. S., Leyva-Jimenez, F. J., & Dall'acqua, S. (2020). Valorisation of underexploited Castanea sativa shells bioactive compounds recovered by supercritical fluid extraction with CO2: a response surface methodology approach. *Journal of CO2 Utilization*, *40*, 101194. https://doi.org/10.1016/j.jcou.2020.101194.

Praporscic, I., & MuravetchiV, V. E. (2004). Constant rate expressing of juice from biological tissue enhanced by pulsed electric field. *Drying Technology*, *22*, 1–14.

Prestes, A. A., Canella, M. H. M., Helm, C. V., da Cruz, A. G., & Prudencio, E. S. (2023). The use of cold pressing technique associated with emerging non-thermal technologies in the preservation of bioactive compounds in tropical fruit juices: An overview. *Current Opinion in Food Science*, *51*, 101005. https://doi.org/10.1016/j.cofs.2023.101005.

Priyanka, K. S. (2018). Influence of operating parameters on supercritical fluid extraction of essential oil from turmeric root. *Journal of Cleaner Production*, *188*, 816–824. https://doi.org/10.1016/j.jclepro.2018.04.052.

Priyanka, K. S. (2020). Selection of suitable model for the supercritical fluid extraction of carrot seed oil: a parametric study. *Lwt*, *119*, 108815. https://doi.org/10.1016/j.lwt.2019.108815.

Puértolas, E., Luengo, E., Álvarez, I., & Raso, J. (2012). Improving mass transfer to soften tissues by pulsed electric fields: Fundamentals and applications. *Annual Review of Food Science and Technology*, *3*(1), 263–282.

Qiu, L., Zhang, M., Tang, J., Adhikari, B., & Cao, P. (2019). Innovative technologies for producing and preserving intermediate moisture foods: A review. *Food Research International*, *116*, 90–102. https://doi.org/10.1016/j.foodres.2018.12.055.

Rahaman, T., Vasiljevic, T., & Ramchandran, L. (2016). Effect of processing on conformational changes of food proteins related to allergenicity. *Trends in Food Science & Technology*, *49*, 24–34.

Ramya, V., & Jain, N. K. (2017). A review on osmotic dehydration of fruits and vegetables: An integrated approach: Osmo-dehydration of fruits and vegetables. *Journal of Food Process Engineering*, *40*(3), 124–140. https://doi.org/10.1111/jfpe.12440.

Rebolleda, S., Rubio, N., Beltrán, S., Sanz, M. T., & González-Sanjosé, M. L. (2012). Supercritical fluid extraction of corn germ oil: Study of the influence of process parameters on the extraction yield and oil quality. *Journal of Supercritical Fluids*, *72*, 270–277. https://doi.org/10.1016/j.supflu.2012.10.001.

Roobab, U., Aadil, R. M., Madni, G. M., & Bekhit, A.E.-D. (2018). The impact of nonthermal technologies on the microbiological quality of juices: A review. *Comprehensive Reviews in Food Science and Food Safety*, *17*, 437–457.

Rushdi, S., Hameed, K. K., Janna, H., & Al-Sharify, Z. T. (2020). Investigation on production of sustainable activated carbon from walnuts shell to be used in protection from COVID-19 disease. *Journal of Green Engineering*, *10*(10), 7517–7526. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85096513484&partnerID=40&md5=916c96e572eaa3335d48fb835753ced2.

Sabarez, H. T. (2018). Thermal drying of foods. In A. Rosenthal, R. Deliza, J. Welti-Chanes, & G. V. Barbosa-Cánovas (Eds.), *Fruit Preserv* (pp. 181–210). Springer. https://doi.org/10.1007/978-1-4939-3311-2_7.

Salea, R., Veriansyah, B., & Tjandrawinata, R. R. (2017). Optimization and scale-up process for supercritical fluids extraction of ginger oil from Zingiber officinale var. Amarum. *The Journal of Supercritical Fluids*, *120*, 285–294. https://doi.org/10.1016/j.supflu.2016.05.035.

Santana, Á. L., & Meireles, M. A. A. (2023). Valorization of cereal byproducts with supercritical technology: The case of corn. *Processes*, *11*(1), 289. https://doi.org/10.3390/pr11010289.

Santillana Farakos, S. M., Frank, J. F., & Schaffner, D. W. (2013). Modeling the influence of temperature, water activity and water mobility on the persistence of Salmonella in low-moisture foods. *International Journal of Food Microbiology*, *166*(2), 280–293. https://doi.org/10.1016/j.ijfoodmicro.2013.07.007.

Santos, O. V., Lorenzo, N. D., Souza, A. L. G., Costa, C. E. F., Conceição, L. R. V., & Lannes, S. C. D. S. (2020). CO$_2$ supercritical fluid extraction of pulp and nut oils from Terminalia catappa fruits: thermogravimetric behavior, spectroscopic and fatty acid profiles. *Food Research International*, *139*, 109814. https://doi.org/10.1016/j.foodres.2020.109814.

Saravacos, G. D. (1997). Moisture transport properties of foods. In *Advances in food engineering* (pp. 58–67). Purdue University.

Saxena, A., Tripathi, B. P., Kumar, M., & Shahi, V. K. (2009). Membrane-based techniques for the separation and purification of proteins: An overview. *Advances in Colloid and Interface Science*, *145*, 1–22. https://doi.org/10.1016/j.cis.2008.07.004.

Shakor, A. M. (2022). When wireless technologies faces COVID-19: Via Apps using to combat the pandemic and save the economy. *Tikrit Journal of Engineering Sciences*, *29*(2), 41–50. https://doi.org/10.25130/tjes.29.2.6.

Silva, E. K., Meireles, M. A. A., & Saldaña, M. D. A. (2020). Supercritical carbon dioxide technology: A promising technique for the non-thermal processing of freshly fruit and vegetable juices. *Trends in Food Science & Technology*, *97*, 381–390. https://doi.org/10.1016/j.tifs.2020.01.025.

Spilimbergo, S., & Bertucco, A. (2003). Non-thermal bacteria inactivation with dense CO$_2$. *Biotechnology and Bioengineering*, *84*, 627–638. https://doi.org/10.1002/bit.10783.

Sun, X., Zhang, W., Zhang, L., Tian, S., & Chen, F. (2020). Molecular and emulsifying properties of arachin and conarachin of peanut protein isolate from ultrasound-assisted extraction. *Lwt*, *132*, 109790. https://doi.org/10.1016/j.lwt.2020.109790.

Sun, J., Uwishema, O., Kassem, H., Abbass, M., Uweis, L., Rai, A., El Saleh, R., Adanur, I., & Onyeaka, H. (2022). Ebola virus outbreak returns to the Democratic Republic of Congo: An urgent rising concern. *Annals of Medicine and Surgery*, *79*, 103958. https://doi.org/10.1016/j.amsu.2022.103958.

Teissie, J., Eynard, N., Vernhes, M. C., Benichou, A., Ganeva, V., et al. (2002). Recent biotechnological developments of electropulsation. A prospective review. *Bioelectrochemistry*, *55*, 107–12.

Temelli, F., Saldaña, M. D. A., & Comin, L. (2012). Application of supercritical fluid extraction in food processing. In J. Pawliszyn (Ed.), *Comprehensive sampling and sample preparation* (Vol. 4, pp. 415–40). Elsevier. https://doi.org/10.1016/B978-0-12-381373-2.00142-3.

Toepfl, S., Heinz V., Knorr, D. (2006). *Application of pulsed electric field technology for the food industry*. pp. 197–22.

Torres-Ossandón, M. J., Vega-Gálvez, A., López, J., Stucken, K., Romero, J., & Di Scala, K. (2018). Effects of high hydrostatic pressure processing and supercritical fluid extraction on bioactive compounds and antioxidant capacity of Cape gooseberry pulp (Physalis peruviana L.). *Journal of Supercritical Fluids*, *138*, 215–220. https://doi.org/10.1016/j.supflu.2018.05.005.

Troy, D. J., Ojha, K. S., Kerry, J. P., & Tiwari, B. K. (2016). Sustainable and consumer-friendly emerging technologies for application within the meat industry: An overview. *Meat Science*, *120*, 2–9.

Tsong, T. Y. (1991). Electroporation of cell membranes. *Biophysical Journal*, *60*, 297–309.

Uwishema, O., Adriano, L. F., Chalhoub, E., Onyeaka, H., Mhanna, M., David, S. C., Nasrallah, Y., Ribeiro, L. L. P. A., & Berjaoui, C. (2021). Bird flu outbreak amidst COVID-19 pandemic in South Africa: Efforts and challenges at hand. *Journal of Medical Virology*, *93*(10), 5676–5679. https://doi.org/10.1002/jmv.27124.

Uwishema, O., Taylor, C., Lawal, L., Hamiidah, N., Robert, I., Nasir, A., Chalhoub, E., Sun, J., Akin, B. T., Adanur, I., Mwazighe, R. M., & Onyeaka, H. (2022). The syndemic burden of HIV/AIDS in Africa amidst the COVID-19 pandemic. *Immunity, Inflammation and Disease*, *10*(1), 26–32. https://doi.org/10.1002/iid3.544.

Uwishema, O., Chalhoub, E., Torbati, T., David, S. C., Khoury, C., Ribeiro, L. L. P. A., Nasrallah, Y., Bekele, B. K., & Onyeaka, H. (2022). Rift Valley fever during the COVID-19 pandemic in Africa: A double burden for Africa's healthcare system. *Health Science Reports*, *5*(1), e468. https://doi.org/10.1002/hsr2.468.

Uwishema, O., Chalhoub, E., Zahabioun, A., David, S. C., Khoury, C., Al-Saraireh, T. H., Bekele, B. K., Mwazighe, R. M., & Onyeaka, H. (2022). The rising incidence of African swine fever during the COVID-19 pandemic in Africa: Efforts, challenges and recommendations. *International Journal of Health Planning and Management*, *37*(1), 561–567. https://doi.org/10.1002/hpm.3357.

Uwishema, O., Adekunbi, O., Peñamante, C. A., Bekele, B. K., Khoury, C., Mhanna, M., Nicholas, A., Adanur, I., Dost, B., & Onyeaka, H. (2022). The burden of monkeypox virus amidst the Covid-19 pandemic in Africa: A double battle for Africa. *Annals of Medicine and Surgery*, *80*, 10419. https://doi.org/10.1016/j.amsu.2022.104197.

Valdramidis, V. P., & Koutsoumanis, K. P. (2016). Challenges and perspectives of advanced technologies in processing, distribution and storage for improving food safety. *Current Opinion in Food Science*, *12*, 63–69.

Vorobiev, E., & Lebovka, N. I. (2006). Extraction of intracellular components by pulsed electric fields. *See Raso & Heinz*, *2006*, 153–193.

Welti-Chanes, J., Vergara-Balderas, F., & Bermúdez-Aguirre, D. (2005). Transport phenomena in food engineering: Basic concepts and advances. *Journal of Food Engineering*, *67*, 113–128.

Yadav, A. K., & Singh, S. V. (2014). Osmotic dehydration of fruits and vegetables: A review. *Journal of Food Science and Technology*, *51*(9), 1654–1673. https://doi.org/10.1007/s13197-012-0659-2.

Zaid, H., Al-sharify, Z., Hamzah, M. H., & Rushdi, S. (2022). Optimization of different chemical processes using response surface methodology-a review: Response surface methodology. *Journal of Engineering and Sustainable Development*, *26*(6), 1–12. https://doi.org/10.31272/jeasd.26.6.1.

Zhang, F., Tian, M., Du, M., & Fang, T. (2017). Enhancing the activity of pectinase using pulsed electric field (PEF) treatment. *Journal of Food Engineering*, *205*, 56–63. https://doi.org/10.1016/j.jfoodeng.2017.02.023.

Zhang, Z. H., Han, Z., Zeng, X. A., & Wang, M. S. (2017). The preparation of Fe-glycine complexes by a novel method (pulsed electric fields). *Food Chemistry*, *219*, 468–476. https://doi.org/10.1016/j.foodchem.2016.09.129.

Zhong, S., Vendrell-Pacheco, M., Heskitt, B., Chitchumroonchokchai, C., Failla, M. L., Sastry, S. K., Francis, D. M., Martin-Belloso, O., Elez-Martinez, P., & Kopec, R. E. (2019). Novel processing technologies as compared to thermal treatment on the bioaccessibility and Caco-2 cell uptake of carotenoids from tomato and kale-based juices. *Journal of Agriculture and Food Chemistry*, *67*, 10185–10194.

Zhu, F. (2018). Modifications of starch by electric field based techniques. *Trends in Food Science & Technology*, *75*, 158–169. https://doi.org/10.1016/j.tifs.2018.03.011.

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