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COMPREHENSIVE REVIEW

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Review of osmotic dehydration: Promising technologies for enhancing products' attributes, opportunities, and challenges for the food industries

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Abstract

Osmotic dehydration (OD) is an efficient preservation technology in that water is removed by immersing the food in a solution with a higher concentration of solutes. The application of OD in food processing offers more benefits than conventional drying technologies. Notably, OD can effectively remove a significant amount of water without a phase change, which reduces the energy demand associated with latent heat and high temperatures. A specific feature of OD is its ability to introduce solutes from the hypertonic solution into the food matrix, thereby influencing the attributes of the final product. This review comprehensively discusses the fundamental principles governing OD, emphasizing the role of chemical potential differences as the driving force behind the molecular diffusion occurring between the food and the osmotic solution. The kinetics of OD are described using mathematical models and the Biot number. The critical factors essential for optimizing OD efficiency are discussed, including product characteristics, osmotic solution properties, and process conditions. In addition, several promising technologies are introduced to enhance OD performance, such as coating, skin treatments, freeze-thawing, ultrasound, high hydrostatic pressure, centrifugation, and pulsed electric field. Reusing osmotic solutions to produce innovative products offers an opportunity to reduce food wastes. This review explores the prospects of valorizing food wastes from various food industries when formulating osmotic solutions for enhancing the quality and nutritional value of osmotically dehydrated foods while mitigating environmental impacts.

KEYWORDS

Biot number, osmotic dehydration, quality of dehydrated products, valorization of food wastes

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1 | INTRODUCTION

The application of drying technologies provides the benefit of prolonging the shelf life of foods without the need for refrigeration, resulting in cost savings in storage, packaging, and transportation. Drying process also ensures product availability beyond the harvest season. Conventional drying technologies, such as air drying, use heat to eliminate moisture from food through evaporation. However, during conventional drying, the thermal degradation of chemical compounds can adversely affect the nutritional value and sensory attributes of the dried products. Therefore, the food industry requires strategies to address the limitations of conventional drying technologies (Aghajanzadeh et al., 2023; Fellows, 2022). Applying technologies that operate at mild temperatures can effectively mitigate the drawbacks of conventional thermal treatment, while also decreasing energy costs. Osmotic dehydration (OD) has emerged as a promising solution to these challenges. Generally, OD decreases the moisture content of foods by approximately 30%–40% (Ahmed, Qazi, et al., 2016; Yadav & Singh, 2014). Because OD does not sufficiently reduce the moisture content of a product, making it shelf-stable at ambient temperatures, supplementary processing steps, such as air-drying, freeze-drying, and vacuum-drying, are necessary. The initial reduction in moisture content during OD decreases the load on the subsequent drying equipment, resulting in low capital expenditure, energy savings, extended machinery longevity, and improved cost-effectiveness (Angilelli et al., 2015). In addition, during OD, water is removed without undergoing a phase change, resulting in low energy consumption (Manzoor et al., 2023).

The other advantage of OD is associated with the absorption of solutes by the food, leading to an improvement in the taste and sensory attributes of the final products (Rahman & Perera, 2007). One notable benefit of OD is the absence of oxidation owing to the oxygen-free environment used when immersing the products in an osmotic solution (Chandra & Kumari, 2015). This effectively prevents enzymatic and oxidative discoloration, eliminating the need for the use of chemicals, such as sulfur dioxide, or a blanching process to preserve food quality. By operating at temperatures ≤50°C, OD is effective in avoiding heat-induced damage and preventing the occurrence of browning reactions (Akbarian et al., 2014).

Although OD offers several advantages, there are some drawbacks that limit its application at an industrial scale (Pandiselvam et al., 2022). Indeed, the main challenges associated with OD are related to long processing time, solute uptake, and reuse of the osmotic solution. Thus, several studies have been carried out in an attempt to mitigate these challenges (Akbarian et al., 2014; Jalaee et al., 2011; Kowalska et al., 2021; Phisut, 2012). Process duration is critical, especially when processing thick and dense foods or products with skin. For this type of product, the long processing time makes OD technology not economically viable at large-scale production. To address processing time concerns, mathematical models are used as a tool to optimize the rate of osmotic mass transfer (Assis et al., 2016; Bchir et al., 2012). Furthermore, combining OD with promising technologies, such as freezing (Zongo et al., 2022), ultrasound (US) (Cichowska et al., 2019), pulsed electric field (PEF) (Amami et al., 2014), high hydrostatic pressure (HHP) (Verma et al., 2014), pulsed vacuum (de Jesus Junqueira et al., 2017), and centrifugal treatments (Barman & Badwaik, 2017), could be effective to address this issue. With respect to possible solute uptake, some studies have explored the use of low-calorie ingredients (e.g., xylitol, D-allulose, fructooligosaccharides, stevia, inulin, mannitol, erythritol, and maltitol) (de Mendonça et al., 2016; Kowalska et al., 2020) or non-purified sweeteners (e.g., maple syrup, honey, agave syrup, or fruit juice concentrates) (Kaur, Singh, et al., 2022) (Table 1). Other investigations have explored coating technology (Rahman et al., 2020).

Several reviews have highlighted the importance of OD in food processing (Ahmed, Qazi, et al., 2016; Pan et al., 2003; Ramya & Jain, 2017; Shi & Le Maguer, 2002); however, limited attention has been paid to specific facets of OD, such as the effects of edible coatings (Kowalska et al., 2021), solute transfer mechanisms (Muniz-Becera et al., 2017), and mathematical models (Assis et al., 2016). Notably, there are gaps in the literature regarding the importance of the Biot number, strategies for minimizing sugar uptake during OD, and revalorization of food waste in the context of OD. Therefore, this review addressed and bridged these gaps by introducing various factors that influence OD. To present a comprehensive understanding, mathematical modeling and the Biot number were introduced to describe the kinetics of OD. Additionally, it investigated how these technologies affect critical factors in mass transfer, including chemical potential, and analyzed promising technologies that influence the effectiveness of OD. Finally, the review sheds light on the opportunities and challenges of OD facing the food industry.

2 | OSMOTIC DEHYDRATION

2.1 | Definition

OD is a mass transfer process employed in food preservation. This process involves immersing a cellular food matrix in a concentrated osmotic solution to reduce its

TABLE 1 Osmotic dehydration conditions for different fruits and vegetables.

Product	Solute	Concentration	Product: Solution	Time	Temperature (°C)	Pretreatment	Shape/Size	Reference
Apple	Stevia	25% and 50%	1:4	10–60 min	30	Ultrasound	Slice	Oliveira et al. (2012)
	Sucrose and Nacl	30%–45% sucrose, 10% NaCl	-	2–8 h	27	None	Slice (1.5 mm)	Monnerat et al. (2010)
	Fructooligosaccharide and sucrose	40%–70%	1:10	20–40 min	40–60	None	Cube (10 mm)	Matusek et al. (2008)
Mango	Sucrose, acid ascorbic (1%), or calcium chloride (1%)	45 °Brix	1:10	15 h	25	None	Cylinder (5 mm)	Guiamba et al. (2016)
	Inulin, piquin-pepper, oleoresin, Tween 80, and sucrose	60 °Brix	1:30	2 h	30–50	None	Slice ($30 \times 25 \times 5$ mm^3)	Jiménez-Hernández et al. (2017)
	Sucrose, glucose, fructose, agave syrup, agave syrup, xanthan gum (0.1% or 0.3%), agave syrup, inulin (5%), and corn syrup	60 °Brix	1:100	4–8 h	40	None	Cube (4–15 mm)	Zongo et al. (2021)
Melon	Sucrose (42%) and fructooligosaccharides (18%)	60 °Brix	1:25	1–28 h	20	None	Pyramid	Angilelli et al. (2015)
Pears	Sucrose and trehalose	25 °Brix	-	1 h	Room temperature	Ascorbic acid (1%)	Cube (5 mm)	Komes et al. (2007)
Pineapples	Fructooligosaccharides, sucrose, and inuline	60 °Brix	1:4	2 h	60	None	Cube (5 mm)	Maldonado et al. (2020)
Pumpkin	Glycerol (40%), trehalose (10%), galacto-oligosaccharides (10%), ascorbic acid, sodium, and calcium chloride mixed with strained yogurt whey or pure water	60 °Brix	-	10–240 min	35–55	None	Parallelepiped ($20 \times 20 \times 5$ mm^3)	Dermesonlouoglou et al. (2020)
Strawberries	Sucrose Mannitol Sorbitol	50% 20%–30% 20%–40%	1:4	3 h	30	None	Slice (5 mm)	Wiktor et al. (2022)
Tomato	Sucrose and NaCl	51.6%–68.4% sucrose 1.6%–3.3% Nacl	1:5	2–22 h	20	Blanching (20 s)	Whole (6 mm)	Derossi et al. (2015)
	Sucrose	50–70 °Brix	>1:40	20–320 min	35–55	None	Slices (4–8 mm)	Bui (2009)
Yacon	Glycerol, maltodextrin, polydextrose, sorbitol	30.2–37.2 °Brix	1:12	6 h	23	None	Discs (5 mm thickness)	Brochier et al. (2015)
	Xylitol, maltitol, erythritol, isomalt, and sorbitol	40 °Brix	1:10	2 h	25	Citric acid (1%)	Slice (5 mm)	Mendonça et al. (2017)

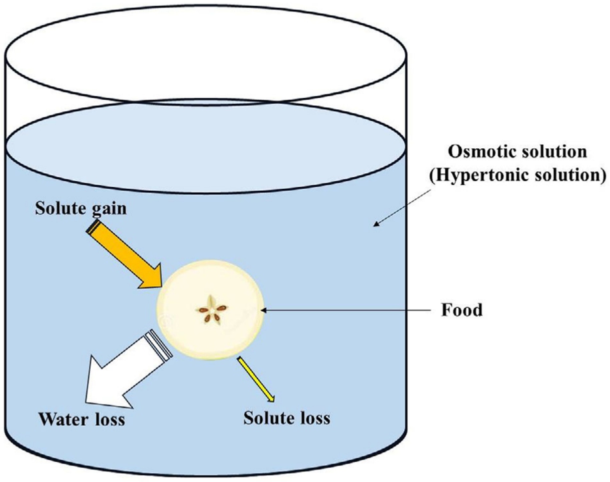


FIGURE 1 Illustration of mass transfer during osmotic dehydration. *Source*: Adapted from Torreggiani (1993).

water activity (Sulistyawati et al., 2018). Indeed, during OD, food is immersed in a hypertonic solution, typically containing sugars and/or salts. Owing to the difference in solute concentration, water is released from the food into the solution, leading to a decrease in food moisture content. The primary driving force for the mass transfer of water molecules is the gradient in chemical potential between the solutions found on both sides of food cell membranes, that is, the osmotic solution and intracellular fluid (Floury et al., 2008). If the membrane is perfectly semipermeable, the solute cannot diffuse into the cells. However, it is difficult to obtain a perfect semipermeable membrane for food systems because of their complex internal structures. Consequently, there is always some degree of solute diffusion into the food and leaching. As illustrated in Figure 1, mass transfer during OD is a complex phenomenon involving the simultaneous transfer of water and solutes and characterized by three counter-current transfer phenomena (Manzoor et al., 2023):

- Water loss (WL): The diffusion of water from the cell protoplasts of the food into a concentrated solution, passing through the cell wall, which acts as a semipermeable membrane. This water diffusion continues until chemical potential equilibrium is achieved.
- Solute gain (SG): The entry incorporation of solutes from the osmotic solution into the food.
- Solid loss (SL): The release of food solutes (e.g., organic acids, minerals, and vitamins) into an osmotic solution (Ramya & Jain, 2017).

It is worth noting that the amount of solid loss is relatively minimal compared to the water loss (WL) and solute gain (SG) phenomena (Bui, 2009).

2.2 | Chemical potential as a driving force for mass transfer

Chemical potential refers to the energy state of 1 mol of a substance (Lewicki & Lenart, 2006). In a solution, the interactions between the solvent (usually water) and solute define the thermodynamic state of the water within the solution (Bui, 2009). The energy state of each substance (water and solute) plays a crucial role in these interactions. The chemical potential represents the amount of energy required to adjust the number of particles in a system while maintaining constant temperature and pressure. Control of the chemical potential is critical for the design of efficient OD processes. This can be achieved by adjusting different parameters, such as solute concentration, temperature, pressure, and immersion time (Giannakourou et al., 2020). Additionally, the choice of solute in the hypertonic solution significantly affects OD because the chemical potential of the solute determines the rate and extent of water removal.

The normalized concentrations of water and sugar in food products and osmotic solutions during OD are shown in Figure 2. The transfer of water and solutes is influenced by the continuous chemical potential difference that persists throughout the process. During OD, the product loses water and gains solutes from the osmotic solution, leading to an increase in its solid content. In contrast, the concentration of the osmotic solution decreases due to the solutes migrating toward the product, and water is released from the product into the solution. The difference in chemical potential provides the driving force behind the movement of particles from areas of higher chemical potential to areas with lower chemical potential, ultimately leading to a state of equilibrium. The chemical potential gradient ($\nabla\mu_i$), closely linked to the concentration gradient, represents the force applied on each penetrant molecule during OD, as indicated in the following equation (Peterlin, 1985):

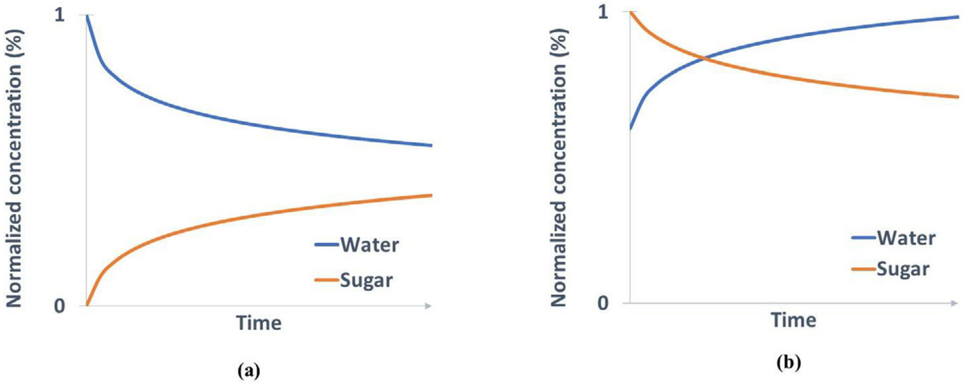
$$\vec{J_i} = -\frac{c_i}{\beta}\nabla\mu_i \tag{1}$$

where $\vec{J_i}$ is diffusion flux, and c_i and β represent the concentration and frictional resistance, respectively.

According to Equation (1), at equilibrium ($\vec{J_i} = 0$), there is no net movement of particles, and the chemical potential becomes uniform throughout the system.

At constant temperature and pressure, the chemical potential (μ) can be expressed according to the following equation (Struchtrup & Struchtrup, 2014):

$$\mu = \left(\frac{\partial G}{\partial n}\right)_{T,\,P} \tag{2}$$



(a)

(b)

FIGURE 2 Normalized concentration of water and sugar in (a) food product and (b) osmotic solution during osmotic dehydration.

where $\frac{\partial G}{\partial n}$ represents the partial derivative of the ratio of Gibbs free energy to the number of moles (n) of the component. Under isothermal conditions, osmosis relies on balancing the energy levels of the two systems, which is achieved by adjusting the pressure or concentration. The extra pressure needed to reach this equilibrium state is referred to as "osmotic pressure" (Lewicki & Lenart, 2006). The osmotic pressure increases with a decrease in the molar mass of the solute and an increase in the concentration of the solution (Lewicki & Lenart, 2006; Rastogi et al., 2002). The chemical potential in the liquid phase, considering the effects of temperature and water activity (a_w), can be calculated according to the following equation (Labuza & Altunakar, 2020):

$$\mu = \mu^\circ + RT\ln(a_w) \tag{3}$$

where μ° represents the standard chemical potential, R corresponds to the universal gas constant (J/K/mol), and T and a_w represent the temperature (K) and water activity of the substance in the liquid phase, respectively.

2.3 | Role of plant cell structure in mass transfer

In OD treatment of fruits and vegetables, mass transfer is greatly influenced by the structural characteristics of the plant tissue, which is predominantly composed of individual cells (Muniz-Becera et al., 2017). A typical plant cell is characterized by two main components: the cell wall and the protoplast. The cell wall facilitates the movement of water and low molecular weight solutes into and out of the cells (Lewicki & Lenart, 2006). The protoplast, which is surrounded by a plasmalemma, comprises various components such as vacuoles, nuclei, and plastids. Generally, during OD, the mass transfer occurs through three different pathways within plant cells (Fito & Chiralt, 2003; González-Pérez et al., 2021; Shi & Le Maguer, 2002):

- The apoplastic pathway facilitates the movement of water and solutes across the cell wall and intercellular spaces through diffusion (González-Pérez et al., 2021). This pathway involves the movement of substances outside the protoplast using the spaces between the cell walls.
- The symplastic pathway involves cell-to-cell transport through specific channels known as plasmodesmata (Shi & Le Maguer, 2002). These channels connect the cytoplasm of adjacent cells, facilitating the transfer of water and solutes between them.
- The transmembrane pathway characterizes the exchange of substances across the cell membrane, involving both the cellular interior (cytoplasm and vacuoles) and exterior (cell wall and intercellular spaces) (González-Pérez et al., 2021).

The cell membrane is permeable to water and is selectively permeable to other solutes. This selectivity arises from the ability of the membrane to differentiate among solutes based on factors, such as ionic properties, size, and electrochemical attributes (Muniz-Becera et al., 2017). Under normal conditions, the cell membrane facilitates the osmotically controlled movement of water and solutes within the plant cells (Spiess et al., 2002). However, when plant tissues are exposed to high osmotic pressure caused by immersion in a hypertonic solution, WL occurs, leading to shrinkage and detachment of the cell membrane from the cell wall, which affects the texture, nutritional value, and organoleptic properties of the final products (Bui, 2009).

3 | FACTORS AFFECTING OSMOTIC DEHYDRATION

3.1 | Product characteristics

The physical and chemical properties of the food matrix significantly influence the efficiency of OD. Understanding and manipulating these properties are essential for optimizing OD and achieving the desired product quality. Physical properties include shape, size, void proportion in the cell wall, membrane permeability, tortuosity, and the presence of skin. These factors influence the pathways and rates of mass transfer during OD. For example, applying the US to the food matrix before OD enhances the movement of solutes and water by generating microchannels. During OD, the geometry and thickness of the food significantly influence the rate of water removal, which is usually attributed to variations in the ratio of surface area to thickness (Tortoe, 2010). Van Nieuwenhuijzen et al. (2001) investigated the impact of cylindrical apple slice diameters (12, 17, and 20 mm) on mass transfer during OD using a sucrose solution (34–63 °Brix). They found that the rates of WL and SG decreased with an increase in sample size, consistent with other observations in pumpkins (Kvapil et al., 2021) and mangoes (Zongo et al., 2021).

The chemical components and ripening stages of foods can influence their mass transfer rates (Sulistyawati et al., 2018). Ripening-induced biochemical changes, such as pectin solubilization and depolymerization of cell walls through the action of hydrolases (Yashoda et al., 2007), cause fruit softening and decreased firmness. This reduced firmness leads to lower internal resistance to WL and SG. Therefore, to ensure consistent and standardized OD results, it is crucial to consider the chemical composition and concentration of food compounds, particularly the maturity and ripeness level of the fruits or vegetables being processed (González-Pérez et al., 2021).

3.2 | Properties of the osmotic solution

3.2.1 | Solute

Cost, taste, compatibility with the food flavor, and preservative properties are all important in the selection of osmotic solutes (Torreggiani, 1993). Sucrose is the common solute employed for plant-based foods owing to its cost-effectiveness and availability (Chen et al., 2007). However, glucose (Chenlo et al., 2002), fructose (Barman & Badwaik, 2017; Kotovicz et al., 2014; Leahu et al., 2020), high-fructose corn syrup (Beaudry et al., 2003), maltose (Chottamom et al., 2012), maltodextrin (Li et al., 2017), and glycerol (Barman & Badwaik, 2017; Brochier et al., 2015) are also used. Ongoing research is focused on replacing sucrose with low-calorie alternatives and on the health benefits of the final product. For example, solutes such as polyols (e.g., xylitol, maltitol, sorbitol, and erythritol), polydextrose, fructooligosaccharides, and inulin are employed, either individually or in combination, to produce multicomponent osmotic solutions (Table 1). By partially (Angilelli et al., 2015; Jiménez-Hernández et al., 2017; Maldonado et al., 2020) or completely (Brochier et al., 2015; Mendonça et al., 2017) substituting sucrose, some functional properties, such as prebiotic effects, reduced calorie content, and improved organoleptic properties, can be achieved. Furthermore, there is growing interest in utilizing nutritious non-purified sweeteners instead of refined sugars (Chauhan et al., 2011; Zongo et al., 2021). These sweeteners not only provide a desirable taste but also contribute to the nutritional value of the final product. For instance, agave syrup is characterized by antibacterial properties (methylglyoxal) and possesses antioxidants, prebiotics (inulin), and a low glycemic index (Escobosa et al., 2014). However, it is essential to conduct economic assessments, particularly in the case of large-scale production of osmotically dehydrated products, using these hypertonic solutions to evaluate their profitability.

Salts are commonly used as osmotic solutes, particularly in vegetable processing. The formation of chemical bonds between ionic solutes (salts) and the plant tissue matrix modifies the resistance of the cell wall and membrane, thereby aiding the diffusion of ionic solutes (Muniz-Becera et al., 2017). Generally, salts with low molecular weights (e.g., NaCl, KCl, and $CaCl_2$) exhibit greater ease of diffusion into plant cells than sucrose solutions with a higher molecular weight (Chandra & Kumari, 2015; Tortoe, 2010). The diffusion of polar molecules, such as sugars, is hindered by the resistance of the cell membrane. Consequently, solutes, including sucrose, tend to form a surface layer on plant tissues, slowing the diffusion of solutes and water compared to that of salts (Chandra & Kumari, 2015). Typically, a small concentration of salts (1%–15%) is incorporated into sugar solutions to diminish layer formation and enhance kinetics during OD (Bekele & Ramaswamy, 2010; Eren & Kaymak-Ertekin, 2007).

3.2.2 | Viscosity

An inverse relationship exists between the diffusion coefficient of a solution and its viscosity (Rastogi et al., 2002). A solution with higher viscosity presents a greater barrier to mass transfer, leading to a reduction in both WL and SG during OD. Therefore, it is possible to achieve the desired water or solid (sugar or salt) content by adjusting the viscosity of the osmotic solution. Viscosity is influenced by various factors, including solute properties (e.g., molecular weight) and temperature. During the OD of pomegranate arils at different temperatures (35, 45, and 55°C), higher WL and SG were obtained at elevated temperatures because of the reduction in viscosity and subsequent increase in the diffusion coefficient (Mundada et al., 2011). However, processing at high temperatures can result in swelling and plasticizing of cell membranes (Li & Ramaswamy, 2005), potentially leading to loss of cell semipermeability and intensifying the osmotic solute penetration (Ciurzyńska et al., 2016). In addition, heat accelerates the Maillard reaction, resulting in nutrient loss (Pandiselvam et al., 2023)). To mitigate the adverse effects of processing at high temperatures, OD is usually operated below 60°C (Li & Ramaswamy, 2005). Higher concentrations of the osmotic solution or the incorporation of thickening agents, like xanthan gum (Emam-Djomeh et al., 2001) or polydextrose (Brochier et al., 2015), can also increase viscosity. In a study conducted by Emam-Djomeh et al. (2001), adding 0.5 g/L xanthan gum to a sucrose–salt solution resulted in a reduction in SG during the OD of the model agar gel. Zongo et al. (2021) successfully obtained low sugar content in osmotically dehydrated mangoes by adding 0.1%–0.3% of xanthan gum to agave syrup solutions (60 °Brix).

3.2.3 | Concentration

The OD rate is influenced by the concentration of the osmotic solution, as there is a relationship between osmotic pressure, chemical potential, and concentration (Phisut, 2012). Studies by Panagiotou et al. (1999) on apples, kiwis, and bananas demonstrated that raising the concentration of an osmotic solution from 30 to 50 °Brix led to higher WL and SG. Indeed, similar observations regarding the influence of solution concentration on the efficiency of OD were reported for apricots (Ispir & Toğrul, 2009) and pomegranate seeds (Mundada et al., 2011). However, excessively high osmotic solution concentrations can hinder the rate of mass transfer by forming a barrier layer at the interface between the food and solution, especially when sucrose is used (Araya-Farias et al., 2014; Lewicki & Lenart, 2020). Therefore, the osmotic solution concentration is restricted to 50–60 °Brix (Torreggiani, 1993).

3.3 | Process conditions

3.3.1 | The ratio of food to osmotic solution

The ratio between the amount of food and osmotic solution volume is an important factor that affects mass transfer kinetics during OD; typically, ratios of 1:10–1:60 are used. During OD, the solution is diluted by absorbing fruit water; hence, maintaining a constant concentration of the solution is essential, either by the continuous evaporation of excess water or by dissolving additional solutes. Both methods enable the reuse of the same hypertonic solution over multiple cycles (Lewicki & Lenart, 2020). However, the choice between these methods should be made after evaluating factors such as energy consumption and economic assessment of solute costs.

3.3.2 | Time

During OD, both the WL and SG show upward trends over time. Considering the mass transfer rate, the OD process can be divided into three stages. The first stage is referred to as the dynamic period, during which mass transfer undergoes variations until equilibrium is reached. According to Lenart and Lewicki (1987), in the first 30 min to 2 h, there is a rapid rate of WL, which gradually slows, enhancing SG. Equilibrium is attained when the net mass transfer stabilizes over time and becomes zero (Corzo & Bracho, 2006; Lenart & Lewicki, 1987). Achieving equilibrium in the OD process is time-consuming (Saleena et al., 2021); moreover, reaching true equilibrium may not be possible owing to biological factors. Consequently, the term “pseudo-equilibrium stage” is used to describe a state that closely approximates true equilibrium. During the pseudo-equilibrium stage, compositional equilibrium within the samples is typically achieved within 24 h (Li & Ramaswamy, 2010).

During OD, the formation of a solute layer on the surface of the food material and cell shrinkage can lead to reduced rates of mass transfer, long processing time, selectivity loss, and solute penetration into the food material (Ferrando & Spiess, 2001; Mavroudis et al., 1998). The long duration of OD can lead to considerable loss of phenolic components, anthocyanins, and carotenoids due to their migration into the osmotic solution (Pandiselvam et al., 2022). The possible dissolution of pectin, along with turgor loss and volumetric shrinkage, could result in reduced plant tissue firmness during prolonged OD (Kucner et al., 2014; Pandiselvam et al., 2022). These changes can adversely affect the organoleptic properties of the final product (Pandiselvam et al., 2022). On the contrary, removing the desired amount of water during a short time can result in enhancing processing efficiency and product quality as well as reducing production costs by saving labor and energy consumption during the drying process (Yu et al., 2017). Therefore, the application of faster drying technology following OD is recommended to mitigate more losses in food quality and minimize costs.

3.3.3 | Temperature

During OD, temperature changes significantly affect mass transfer (Azuara et al., 1992). The elevated temperature generally accelerates the changes in WL and SG. This can be attributed to several temperature-induced effects, including the release of trapped air within the cellular structure and enhanced cell permeability resulting from tissue swelling and plasticization. These structural changes create a space for water elimination and facilitate the entrance of solutes into food materials (Lazarides et al., 1999). Additionally, high temperatures act as an external resistance to mass transfer by increasing the osmotic pressure and reducing the solution viscosity (Falade & Igbeka, 2007). Lazarides et al. (1999) reported that SG increased (<55%) during OD of apples at temperatures ranging from 30 to 50°C compared to that of processing at room temperature. Similar findings were reported for cashew apples and apples when exposed to higher temperatures (Falade et al., 2003; Kaymak-Ertekin & Sultanoğlu, 2000). Although increasing temperature can enhance mass transfer during OD, it is important to consider the undesirable changes that can occur in plant-based foods at temperatures exceeding 50°C, including the degradation of organoleptic properties and nutritional values. Elevated temperatures during OD can also cause structural modifications (cell wall rupture and collapse) in plant tissues that diminish membrane selectivity and enhance nutrient leaching. For example, during OD at temperatures ranging from 25 to 55°C, the ascorbic acid content of red bell peppers decreased from 20% to 4% of the initial value, and the content of carotenoids declined from 80% to 55% (Ade-Omowaye et al., 2002). Almeida et al. (2015) reported that OD temperatures above 45°C resulted in a 70% reduction in phenolic compounds as well as the darkening of bananas.

3.3.4 | Agitation

During OD, agitation is usually employed to enhance mass transfer and prevent localized dilution of the osmotic solution at the surface of samples (Goula et al., 2017). It also helps to preserve the temperature and concentration uniformity throughout the osmotic solution (Eren & Kaymak-Ertekin, 2007). During OD, the increased agitation of the osmotic solution can lead to higher WL (Rastogi et al., 2002). This increase could be attributed to the effect of agitation in reducing the exterior resistance generated by the viscosity of the osmotic solution close to the food surface (Tortoe, 2010). The effect of agitation on SG depends on the OD duration. Over a short process time, agitation has no significant impact on SG; conversely, agitation can diminish SG over a long process time (Mavroudis et al., 1998). It is important to carefully design agitation methods to prevent the disintegration of fragile fruits. Various techniques such as agitation baths or oscillatory systems can be utilized to induce motion in osmotic solutions during OD, as well as US (Bui, 2009; Goula et al., 2017).

3.3.5 | pH

Contreras and Smyrl (1981) found that acidification (pH = 3) enhanced the WL of apples during OD, and at a lower pH of 2, it led to a softer texture owing to the depolymerization and hydrolysis of pectin (Contreras & Smyrl, 1981). It is important to note that a softer texture resulting from low pH may increase SG in the product (Khin et al., 2005). Besides, lowering the pH aids in the microbiological stabilization of the food product and enhances its color stability by inhibiting enzymatic browning (Chavan et al., 2010). Ascorbic acid and citric acid are the most common acids used for increasing the acidity of the osmotic solution (Chavan et al., 2010). Nevertheless, when selecting an appropriate pH for OD, considering the taste of the final product is crucial (Ahmed, Qazi, et al., 2016). Therefore, determining the optimal pH for OD involves a balance among different aspects, such as the desired texture, microbiological stability, color retention, and taste preference.

4 | OSMOTIC DEHYDRATION KINETICS

4.1 | Mass transfer and efficiency of osmotic dehydration

To measure mass transfer during OD, three parameters, weight reduction (WR), WL, and SG, are usually defined according to the following equations (Pan et al., 2003; Sulistyawati et al., 2018):

$$\mathrm{WR}\ (\%) = 100\,\frac{M_{df} - M_{d0}}{M_{d0}} \tag{4}$$

$$\mathrm{SG}\ (\%) = 100\,\frac{M_{df} - M_{d0}}{M_{0}} \tag{5}$$

$$\mathrm{WL}\ (\%) = 100\,\frac{(M_0 - M_{d0}) - (M - M_{df})}{M_0} \tag{6}$$

where M_0 represents the initial sample mass (kg), M_f is the final sample mass (kg), and M_{d0} and M_{df} are the initial and final masses of the dry matter (kg), respectively. The OD efficiency is determined using (Khin et al., 2005)

$$\text{Efficiency} = \frac{\text{WL}_{eq}}{\text{SG}_{eq}} \tag{7}$$

where WL_{eq} and SG_{eq} are the WL (kg) and SG (kg) under equilibrium conditions, respectively. In OD, the typical objective is to maximize WL and minimize SG. A higher OD efficiency value indicates a greater amount of WL and a lower transfer of solid into the food matrix (Khin et al., 2007). Enhancing efficiency is prioritized to attain desired product properties, such as lower water content, while preventing the absorption of excess solids to protect the food's taste and authenticity. Zongo et al. (2021) and Khin et al. (2007) have calculated the OD efficiencies to assess the performance of various processing conditions of mango and apple, respectively. They observed that OD conditions characterized by low viscosity of osmotic solution, coating the samples, and high molecular size of osmotic agents resulted in higher efficiency values.

4.2 | Mathematical modeling

Mathematical modeling is a helpful tool for understanding the kinetics of OD in food processing, providing a valuable complement to experimental findings. It is possible to use the differential equations of Fick's law (Equation 8) to calculate the effective diffusivities of water and solutes (Shi & Xue, 2008). This approach has been utilized to investigate mass transfer phenomena during the OD of different foods, including paprika (Ade-Omowaye et al., 2002), apples (Jalaee et al., 2011), lemons (Rubio-Arraez et al., 2015), and mango slices (Giraldo et al., 2003). Fick's first law was formulated to describe the diffusion of gases in a single phase. However, Fick's first law can be used to predict mass transfer by considering the principles of molecular diffusion, where the concentration gradient acts as the driving force, as shown in the following equation:

$$J_i = -D_{effi} \frac{\partial C_i}{\partial x} \tag{8}$$

where J_i is the water or solute flux (kg/m^2/s), D_{effi} is the effective diffusion coefficient (m^2/s), C_i is the concentration of compound i (kg/m^3), and x is the diffusion distance (m). The negative sign in Equation (8) shows the diffusion direction, which is opposite to that of the concentration gradient (Crank, 1979). Mass-balance (Equation 9) is derived from Fick's law (Equation 8) and is commonly used to study the kinetics of mass transfer during OD:

$$\frac{\partial C_i}{\partial t} = D_{effi} \frac{\partial^2 C_i}{\partial x^2} \tag{9}$$

The effective diffusion coefficient of the compounds is influenced by the inherent characteristics of the plant tissues and the process temperature, as shown in the following equation (Shi & Xue, 2008):

$$D_{effi} = \frac{D \times \varepsilon}{\tau} + f(T) \tag{10}$$

where D_{effi} denotes the effective diffusion coefficient, ε and τ represent the porosity and tortuosity, respectively, and T stands for the temperature (°C). Therefore, it is essential to recognize that several other factors must be considered for a more accurate description of mass transfer during OD, including the properties of the biological material, the formation of a boundary layer at the tissue interface, shrinkage, and the osmotic solution attributes. To address these complexities and achieve accurate mass transfer, several authors have modified Fick's law by introducing additional important variables. For instance, Bui (2009) considered the effects of shrinkage and the formation of boundary layers at the solute–tissue interface in mass-transfer modeling during the OD of tomatoes. In addition to Fick's law, various alternative mathematical models have been developed to predict mass transfer during the OD of foods. These models can be classified into three categories: empirical, phenomenological, and mechanistic (Assis et al., 2016). The most utilized OD models for olive, apple, pumpkin, broccoli, and mandarin peel are described in Table 2. In an extensive review of mathematical modeling in OD, Assis et al. (2016) used a decision tree to select suitable models based on the osmotic conditions, including the classical or non-classical geometry of the sample, operation pressure (atmospheric or vacuum), processing time (short or long duration), and type of approach (microscopic or equilibrium value). They found that the Azuara, Magee, Page, Peleg, Weibull, and Crank models were the best fit models for conditions involving a microscopic approach, equilibrium values of SG or WL, and atmospheric pressure. Additionally, Crank's model was identified as the best fit model for classical geometries, such as infinite plane sheets, infinite cylinders, and spheres.

In OD, Fick's law is commonly used to predict mass transfer kinetics and diffusion coefficients, assuming that mass transfer occurs purely through diffusion and that any external resistance is negligible. However, external mass transfer can become a dominant factor, especially for viscous solutions (Zongo et al., 2023), and mass transfer can

TABLE 2 Mathematical models used in osmotic dehydration.

Mathematical models	Product	References
Page's: $Y = Y_\infty (1 - \exp(-A.t^B))$ Y: WL or SG Y_∞: WL or SG at equilibrium condition A and B: Page's constants t: Process time	Pomegranate arils Strawberries Squid Apple Pumpkin Mango	Allahdad et al. (2019) Nuñez-Mancilla et al. (2013) Uribe et al. (2011) Mandala et al. (2005) Zenoozian et al. (2008) Sulistyawati et al. (2020)
Magee's: $K = A.C_0^x T^y$ K: Rate parameter A, x, and y: Model constants C_0: Initial solute concentration T: Temperature	Mandarin peel Carrots Broccoli Oyster Mushroom Pumpkin, Kiwi, and Pear Plum	Kaur, Rana, et al. (2022) Deshmukh et al. (2021) Salim et al. (2016) Ramya and Kumar (2015) Arballo et al. (2012) Ibitwar et al. (2008)
Weibull's: $\frac{Y}{Y_\infty} = 1 - \exp[-[\frac{t}{\alpha}]]^\beta$ Y: WL or SG Y_∞: WL or SG at equilibrium condition t: Process time α: Scale parameter showing the time required for $\frac{Y}{Y_\infty}$ reach the value of $(1 - e^{-1})$ β: Shape parameter	Button mushroom Cassava Ginger Mackerel Mango Sardine Apple	Pei et al. (2019) Ayetigbo et al. (2019) Dash et al. (2019) Checmarev et al. (2014) Khan et al. (2008) Corzo and Bracho (2008) Cunha et al. (2001)
Peleg's: $Y = \frac{t}{K_1 + K_2.t}$ Y: WL or SG t: Process time K_1 and K_2: Peleg's constants	Cambuci Jamun fruit Gooseberry Strawberry Cashew apples	Paes et al. (2019) Sharma and Dash (2019) Zapata Montoya et al. (2016) Cheng et al. (2014) Azoubel et al. (2009)
Azuara's: $Y = \frac{S_1 t\ (Y_\infty)}{1 + S_1 t}$ Y: WL or SG $Y_{\infty:}$ WL or SG at equilibrium condition S: Azuara's constant t: Process time	Olive Banana Mapara fillet Apple Sardine Pineapple	Ghellam et al. (2021) Rascón et al. (2018) de Almeida Maciel et al. (2016) Azarpazhooh and Ramaswamy (2012) Corzo and Bracho (2006) Waliszewski et al. (2002)
Crank's: Infinite slab: $\frac{Y}{Y_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp - (2n+1)^2 \frac{\pi^2}{4} \mathrm{F_O}$ Infinite cylinder: $\frac{Y}{Y_\infty} = 1 - \sum_{n=1}^{\infty} \frac{4}{(a^2\ \alpha_n^2)} \exp(-D_e\, \alpha_n^2\, \mathrm{t})$ Sphere: $\frac{Y}{Y_\infty} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-D_e\, n^2\, \frac{\pi^2 - t}{a^2}\right)$ Y: WL or SG $Y_{\infty:}$ WL or SG at equilibrium condition F_O: Fourier number ($F_o = \frac{D_e\, t}{l^2}$) a: Cylinder or sphere radius D_e: Effective diffusivity t: Process time l: Characteristic length	Apple Potato Pumpkin Cherry	Assis et al. (2017), Simpson et al. (2015) Khin et al. (2006) Abraão et al. (2013), Mayor et al. (2006) Maldonado and Pacheco (2022)

(Continues)

TABLE 2 (Continued)

Mathematical models	Product	References
Hydrodynamic mechanism (HDM) model: $-\Delta_p + \frac{32\mu z^2}{D^2} x_v \; \frac{dx_v}{d_t} = 0$ The volumetric fraction of the liquid transferred by the HDM: $x = \varepsilon_e \; x_v$ Δ_p: Pressure variation between the interior and exterior of the pore μ: Liquid viscosity z: Pore length D: Diameter of a cylindric pore x_v: Penetration depth of the liquid into the pore x: Volumetric fraction of the liquid transferred by the HDM ε_e: Effective porosity	Guava	Panadés et al. (2006)

Abbreviations: SG, solute gain; WL, water loss;.

also be dictated simultaneously by both internal and external mechanisms. In these special contexts, using Fick's law is not appropriate; therefore, other alternatives should be explored without suggesting complex mathematical expressions. Recently, a very simple model was developed for predicting dehydration kinetics, which includes both internal and external heat resistances (Nguyen et al., 2023). One suggestion is to investigate the possible adaptation of this type of convenient and practical model, developed for heat transfer, to the mass transfer that occurs during OD.

4.3 | Biot number

During OD, internal and external resistance can simultaneously dictate mass transfer. Internal resistance is associated with the structural characteristics of plant tissues, including the ripeness index, variety, porosity, tortuosity, geometry, and size (Derossi et al., 2011). External resistance is influenced by various properties of the osmotic solution (e.g., viscosity, concentration, temperature, and agitation), solute characteristics (e.g., size, polarity, and ionic nature), and the ratio of the product to the solution. To describe the relationship between the internal and external resistances in mass transfer, various parameters are employed, including the convective mass transfer coefficient, internal diffusion coefficient, sample thickness, and equilibrium relationship at the interface (Bui, 2009). The dimensionless Biot number (Bi_m), calculated as shown in the following equation, provides insight into the importance of both internal and external resistances, thus helping to identify the dominant factor influencing mass transfer during OD (Ratti, 1994):

$$Bi_{\mathrm{m}} = \frac{\textbf{INTERNAL}\text{ resistance of mass transfer}}{\textbf{EXTERNAL}\text{ resistance of mass transfer}} = \frac{K_c L_0}{P_l \rho_s D_{effi}} \tag{11}$$

where K_c and L_0 are the mass transfer coefficients ($\mathrm{kg_{water}/m^2/s/kPa}$) and characteristic length (m), respectively; P_l is the equilibrium relation at the interface ($(\mathrm{kg_{water}/kg_{dry\ matter}})/\mathrm{kPa}$); and ρ_s and D_{effi} refer to dry matter concentration ($\mathrm{kg_{dry\ matter}/m^3}$) and the effective diffusion coefficient ($\mathrm{m^2/s}$), respectively. When the $Bi_{\mathrm{m}} \geq 100$, mass transfer is mainly controlled by in ternal resistance. Conversely, when $Bi_{\mathrm{m}} \leq 0.1$, external resistance becomes the primary factor influencing mass transfer (Dincer & Dost, 1995; Rurush et al., 2022). When $0.1 < Bi_{\mathrm{m}} < 100$, mass transfer is considered to be influenced almost equally by both internal and external resistances (Nguyen et al., 2023). For example, in thick food samples, internal resistance is more likely to be a controlling factor, whereas in thinner samples, external resistance has a greater influence (Pakowski & Mujumdar, 2020). Additionally, the elevated concentration and viscosity of the solution, or the lack of agitation, decrease the Biot number, emphasizing the importance of external resistance under these conditions. Generally, the effect of external resistance is assumed to be insignificant, suggesting that OD control is governed mainly by internal resistance (Angilelli et al., 2015). Pacheco-Angulo et al. (2016) investigated the OD of carrot slices in NaCl solutions under different conditions. They assumed a diffusion-controlled process with agitation and a convective-controlled process without agitation, with different ratios of product to solution. The highest Biot numbers for water (87.9) and solutes (126.7) were reported with agitation at 190 rpm. However, without agitation, Biot numbers were lower, ranging from 21.3 to 28.3 for water and 14.8 to 19.7 for solute (Pacheco-Angulo et al., 2016). However, the importance of external resistance to mass transfer can vary depending on specific OD conditions, such as the concentration, viscosity, and size of the solutes. Therefore, it is important to account for both the internal and external resistances in mass transfer, or at the very least, to determine the predominant resistance.

5 | PROMISING TECHNOLOGIES TO ENHANCE OSMOTIC DEHYDRATION

During OD, resistance to mass transfer could be attributed to the cellular membranes of fruits and vegetables (Dermesonlouoglou et al., 2016). Additionally, the possible release of solutes from food and the uptake of sugar and/or salt by the product can alter its nutritional value. To address these issues, various techniques, such as coating, freezing, US treatment, PEF, HHP, and centrifugation, have been employed (Ahmed, Qazi, et al., 2016). In addition to improving product quality, these techniques aim to increase efficiency, reduce equipment size, minimize energy consumption, and diminish waste generation (Nguyen et al., 2020).

5.1 | Food coating

An edible coating is a thin layer commonly derived from bio-based compounds, such as polysaccharides, proteins, lipids, or their combinations (Kowalska et al., 2021). The choice of an appropriate coating material depends on the quality and characteristics of the final product. In the context of OD, edible coating, as a pretreatment, can act as a barrier to SG gain while ensuring adequate WL (Khin et al., 2005; Mohammadkhani et al., 2024). As shown in Figure 3a, coating is typically performed by immersing the food in a coating solution for less than 1 min (Kowalska et al., 2021). Subsequently, the coated foods can be dipped into a calcium-based solution (e.g., $CaCl_2$ solution), which acts as a stabilizer, before drying for 5–15 min at ambient or high temperatures. In some cases, this procedure can be repeated to achieve double coating. For example, double-coated strawberries showed improved OD efficiency (Matuska et al., 2006). Table 3 shows the application of coating as a pretreatment in the OD process for different fruits and vegetables. The WL was found to be minimally affected by the coating. However, coating improved the performance ratio (WL/SG) for the OD of coated versus uncoated apples (Emam-Djomeh et al., 2006). Jalaee et al. (2011) coated apple rings with low-methoxyl pectin, carboxymethyl cellulose, and corn starch before OD using sucrose solutions (50% and 60%) and noted higher WL/SG ratios. In another study, Azam et al. (2013) applied a novel gluten-based coating to mango cubes at various maturity levels before OD using sucrose solutions (45°, 55°, and 65° °Brix). At 55 °Brix, the coated mangoes showed higher WL than uncoated mangoes. Edible coatings result in low-calorie and high-quality products by limiting sugar uptake, preventing enzymatic browning, minimizing the loss of natural solutes, inhibiting microbiological growth, and improving the overall textural properties of food products (Khin et al., 2005; Kowalska et al., 2021).

5.2 | Freezing and thawing

Many fruits and vegetables are seasonal and not available during the whole year. Therefore, an effective preservative way is to freeze these products after harvest and subsequently process them using other transformation processes, such as OD (Table 3). During freezing, the formation of ice changes the tissue structure through depolymerization of cell walls, cell membrane breakage, and osmotic pressure alteration (Li et al., 2018). Mundada et al. (2011) employed freezing at −18°C for pomegranate arils before OD to increase the permeability of the outer layer, facilitating mass transfer. Similarly, Bchir et al. (2012) froze pomegranate seeds at −50°C before OD in a sucrose solution (55 °Brix) and observed an increase in both WL and SG. Khuwijitjaru et al. (2022) mentioned that freezing or freeze-thawing as a pretreatment for OD could enhance mass transfer, resulting in reduced drying time and improved quality of the final product. Freezing, with or without subsequent thawing, may not significantly improve WL despite the generation of a porous structure, owing to cell collapse and membrane breakage. However, thawing can increase SG because of tissue damage, resulting in the final product having a higher sugar/salt content and negatively impacting its nutritional quality (Zongo et al., 2022).

5.3 | Ultrasound

US refers to mechanical waves that are used in both liquid and solid foods (Ghellam et al., 2021; Nowacka et al., 2014). US technology is categorized into low and high frequencies. High-frequency US (>100 kHz) is characterized by low intensity (<1 W/cm^2) (Mason et al., 2011), making it appropriate for sensitive food products (Aghajanzadeh & Ziaiifar, 2021). On the other hand, the US in the frequency range of 20–100 kHz is characterized by high intensity (>1 W/cm^2) (Mason et al., 2011), leading to possible material disruption. Generally, low-frequency US is used to enhance enzyme inactivation, freezing, extraction, and dehydration (Witrowa-Rajchert et al., 2014). When US is applied simultaneously during OD, the process is called osmosonication. US is typically performed by immersing the food in distilled water in a US bath or by using a US probe in the bath for a short time, usually 10–30 min (Fernandes & Rodrigues, 2009). Figure 3b illustrates the two US operating modes (probe and bath) used in food

TABLE 3 Effects of various pretreatments on the efficiency of osmotic dehydration.

Pretreatment	Product	Pretreatment	OD	Main findings	References
Edible coating	Apple	Basil seed gum (0.3% and 0.6%)	40–60°C, 6 h, and sucrose (40–60 °Brix)	↓ SG	Etemadi et al. (2020)
	Potato and apple	Alginic acid (3%) and polygalacturonic acid (3%)	27°C, 2 h, sucrose and glucose (30%–50%)	↑ WL ↓ SG	Rahman et al. (2020)
	Mango (different ripeness levels)	Gluten in wheat flour	50°C, 2 h, and sucrose (45–65 °Brix)	↑ WL ↑OD efficiency	Azam et al. (2013)
	Apple	Low-methoxyl pectinate (1%–3%) and $CaCl_2$ (2%) CMC (0.5%–2%) and $CaCl_2$ (0.3%) Corn starch (1%–3%) and $CaCl_2$ (2%)	30°C, 3 h, and sucrose (50% and 60%)	↓ WL ↓ SG	Jalaee et al. (2011)
	Papaya (green and ripe)	Chitosan coating: chitosan (1%), lactic acid (1%), and Tween 80 (0.1%) Emulsion chitosan coating film: chitosan (1%), lactic acid (1%), tween 80 (0.1%), and oleic acid (2%)	25°C, 25 h, and sucrose (40 °Brix)	↑OD efficiency	García et al. (2010)
Freezing	Mango	−18°C, 0, 1, or 2 months Thawing before OD: N/A	31°C, 20 h, sucrose (32 °Brix), fructose, ascorbic acid (0.15%), and citric acid (0.2%)	↓ WL ↑ SG ↑ Hardness ↑ Gumminess ↓ Browning	Khuwijitjaru et al. (2022)
		−36°C Thawing before OD: Yes (4°C, 24 h)	40°C, 4 h, agave syrup (60 °Brix), [agave syrup (60°Brix) and inulin (5%)], and [agave syrup (60 °Brix), inulin (5%), and xanthan gum (0.3%)]	↓ WL ↓ SG	Zongo et al. (2022)
	Pomegranate seed	−50°C Thawing before OD: N/A	35–55°C, 0–420 min, sucrose (55 °Brix), and 1:4*	↑ WL ↓ SG	Bchir et al. (2012)
	Pomegranate aril	−18°C and 24 h Thawing before OD: Yes	35–55°C, 0–240 min, sucrose (40–60 °Brix), and 1:4*	↑ SG ↑ WL	Mundada et al. (2011)
Ultrasound	Apple	21 kHz	40°C, 30–180 min, erythritol (30%), xylitol, and maltitol, dihydroxyacetone, and sucrose (50%)	↓ WL ↓Water activity	Cichowska et al. (2019)
	Button mushroom	40 kHz and 200 W	30°C, 75 min, glucose or sucrose (40%–60%), and NaCl (10%–20%)	↑OD efficiency	Pei et al. (2019)
	Ginger	33 kHz, 600 W, 30 min, and 30°C	Sucrose (20%)	↑ Color quality ↑Retention of bioactives	Osae et al. (2019)
	Mango	25 kHz, 55 kW/m^3, and 5–40 min	23°C and sucrose	↑ WL ↑ SG	Fernandes et al. (2019)

(Continues)

TABLE 3 (Continued)

Pretreatment	Product	Pretreatment	OD	Main findings	References
	Persimmon fruit	35 kHz, 480 W, and 10–30 min	30°C and sucrose (45–70 °Brix)	↑ WL ↑ SG ↓ Drying time	Bozkir et al. (2019)
	Potato	20 kHz, 5–29 min, and 20–45°C	Maltodextrin, NaCl (30%–70%), and 3 h	↑ WL ↑ SG	Goula et al. (2017)
	Kiwifruit	35 kHz and 20–30 min	25°C, 2 h, and sucrose (61.5%)	↑ WL	Nowacka et al. (2014)
Pulsed electric field (PEF)	Strawberry	100–400 V/cm, 100 μs, and 100 Hz	25°C, 4 h, sucrose (40%), trehalose (40%), and 1:4*	↑ WL ↓ SG	Tylewicz et al. (2017)
	Kiwifruit	100–400 V/cm, 100 μs, and 100 Hz	25°C, 2 h, sucrose (61.5 °Brix), and 1:4*	↑ WL ↓ SG	Traffano-Schiffo et al. (2016)
		0.7–1.8 KV/cm, 15 μs, and 300 Hz	25–45°C, 4 h, glycerol (30%), maltodextrin (20%), trehalose (10%), ascorbic acid (2%), calcium chloride (1.5%), sodium chloride (1%), citric acid (0.2%), and 1:5*	↑ WL ↑ SG	Dermesonlouoglou et al. (2016)
	Apple, banana, and carrot	Apple: 0.90 kV/cm, 0.75 s, and 100 μs Banana: 0.30 kV/cm, 0.05 s, and 100 μs Carrot: 0.60 kV/cm, 0.05 s, and 100 μs	25°C, 4 h, sucrose (65%), and 1:3*	↑ WL ↑ SG	Amami et al. (2014)
High hydrostatic pressure (HHP)	Mango	0.1–600 MPa and 5°C	4°C, 24 h, sorbitol (20–60 °Brix), Ca_2Lac (0%–2%), and 1:5*	↑ Sorbitol uptake ↓ Lixiviation of bioactives	Lamilla et al. (2021)
	Red abalone	350–550 MPa and 15°C	15°C, 5–10 min, salt (10%–15%), and 1:8*	↑ Mass transfer	Pérez-Won et al. (2016)
	Banana	100–500 MPa, 26°C, and 5 min	30–70°C, 5–9 h, sucrose, and 1:5*	↑ WL ↑ SG	Verma et al. (2014)
	Strawberry	400–500 MPa, 15°C, and 10 min	15°C, 10 min, sucrose (4 °Brix), and 1:4*	↑ Color quality	Nuñez-Mancilla et al. (2013)
Pulsed vacuum (PV)	Eggplant	Vacuum	30°C, 10–360 min, solids (0.1 kg/kg), ascorbic acid and citric acid (2%), and 1:10*	↑ WL ↑ SG ↑ Ion uptake	de Jesus Junqueira et al. (2017)
	Tomato	Vacuum 50 mbar and 10 min	26–27°C, 6–12 h, tomato extract, probiotic suspensions (20–60 °Brix), and 1:1*	↑ Mass transfer ↑ Probiotics infusion	Chottanom et al. (2016)
	Carrots	Pulsed-microwave vacuum, 6.66 kPa, 5 min, and 1 W/g	29–71°C, 6–74 min, sucrose (23%–57%), and 1:10*	↑ OD efficiency	Sutar and Prasad (2011)
Centrifugation	Carambola	2800 rpm and 15–60 min	50°C, 180 min, glucose, sucrose, fructose, glycerol (70 °Brix), and 1:10*	↑ WL ↓ SG	Barman and Badwaik (2017)
	Bamboo shoot	1600–2800 rpm	30–50°C, 120–240 min, and NaCl (5%–25%)	↑ WL	Badwaik et al. (2014)

(Continues)

TABLE 3 (Continued)

Pretreatment	Product	Pretreatment	OD	Main findings	References
Skin Pretreatment	Sea buckthorn	Liquid nitrogen, steam blanching, and freeze cycles	40°C, 6 h, and sucrose (60 °Brix)	↑Mass transfer	Araya-Farias et al. (2014)
	Blueberry	Liquid nitrogen	40°C, 8 h, sucrose (60 °Brix), and 1: 40*	↑Mass transfer	Ketata et al. (2013)

Abbreviations: CMC, carboxymethyl cellulose; OD, osmotic dehydration; SG, solute gain; WL, water loss.
*Ratio of product: solution.

processing. The US mechanism consists of alternate compression and expansion of the medium, resulting in the rapid formation and collapse of bubbles, known as the cavitation phenomenon (Witrowa-Rajchert et al., 2014). When the bubbles collapse near a solid material, they release microjets at a speed of 200 m/s, creating microscopic channels that serve as new paths for moisture movement (Leonelli & Mason, 2010). Therefore, US application increases mass transfer (WL and SG) during OD by developing these microchannels and increasing the porosity of food materials (Salehi et al., 2023). The cavitation causes an accumulation of energy, which generates localized heating and pressure (Pandiselvam et al., 2023; Witrowa-Rajchert et al., 2014). In some cases, this heating can bring softening of the food texture and increase the solubility of extracted compounds. Hence, during US treatment, it is crucial to control temperature raise by adjusting US processing parameters (intensity, frequency, and duration), employing cooling systems (such as circulating water baths or cooling jackets), or precooling the osmotic solution.

When US is applied simultaneously during OD, the process is called osmosonication. US is typically performed by immersing the food in distilled water in a US bath or by using a US probe in the bath for a short time, usually 10–30 min (Fernandes & Rodrigues, 2009). US pretreatment shows promising outcomes in the context of OD (Table 3). Goula et al. (2017) applied US (35 kHz, 30 min) to kiwifruits before OD in a 61.5% sucrose solution and found that US (≥10 min) increased WL and SG. Microscopic analysis of kiwifruit tissue structures revealed the generation of microchannels that facilitated water diffusivity during OD. Wang et al. (2023) also reported that the application of US during OD was effective in improving the calcium content of apples. Additionally, several other studies have reported the positive effects of US on the maintenance of color, bioactive compounds, and the texture of various fruits such as ginger (Osae et al., 2019) and tomatoes (Corrêa et al., 2015). Osmosonication is effective at reducing processing time, enhancing product quality, and improving mass transfer rates during OD (Kroehnke et al., 2021).

5.4 | Pulsed electric field

In the PEF process, the food material is placed inside a treatment chamber equipped with two electrodes in various configurations, such as parallel plates, wire cylinders, rods, rodplates, and coaxial (concentric) cylinders (Aghajanzadeh & Ziaiifar, 2021) (Figure 3c). A high-voltage generator provides pulses of a specific intensity, shape, and duration. Food is subjected to controlled high-voltage electric pulses for short durations, typically falling within the range of microseconds (Aghajanzadeh & Ziaiifar, 2021; Toepfl & Knorr, 2006). The cell membrane inherently possesses a specific dielectric strength. Within the cytoplasm, which contains free ions, the dielectric constant is higher compared to both the cell membrane and the surrounding osmotic solution. This difference shows a transmembrane potential between the cell's interior (cytoplasm) and its exterior (osmotic solution). By the application of PEF, ions migrate along the electrical field and accumulate at the membrane, causing compression, reducing membrane thickness, and increasing transmembrane potential (Buckow et al., 2013). If the applied electrical field intensity surpasses the critical threshold of transmembrane potential, pores of various sizes form in the membrane, disrupting its natural permeability to small molecules and leading to cell swelling and rupture, which is known as electroporation. Therefore, electroporation creates semipermeable tissues, resulting in improved mass transfer during OD ((Balasa, 2016; Gürsul et al., 2016; Vorobiev & Lebovka, 2008). Table 3 provides examples of the effects of PEF pretreatment on the effectiveness of OD. WL generally improves with PEF pretreatment, whereas SG does not show a consistent trend. Using PEF during OD increased the WL and SG of apples, bananas, carrots (Amami et al., 2014), mangoes (Tedjo et al., 2002), and bell peppers (Ade-Omowaye et al., 2002). Although WL was enhanced, Tylewicz et al. (2017) and Traffano-Schiffo et al. (2016) reported low levels of SG for strawberries and kiwifruits, respectively. The variability in the SG highlights the importance of further investigations to optimize PEF parameters, thereby modulating tissue permeability for selective mass transfer and achieving controlled

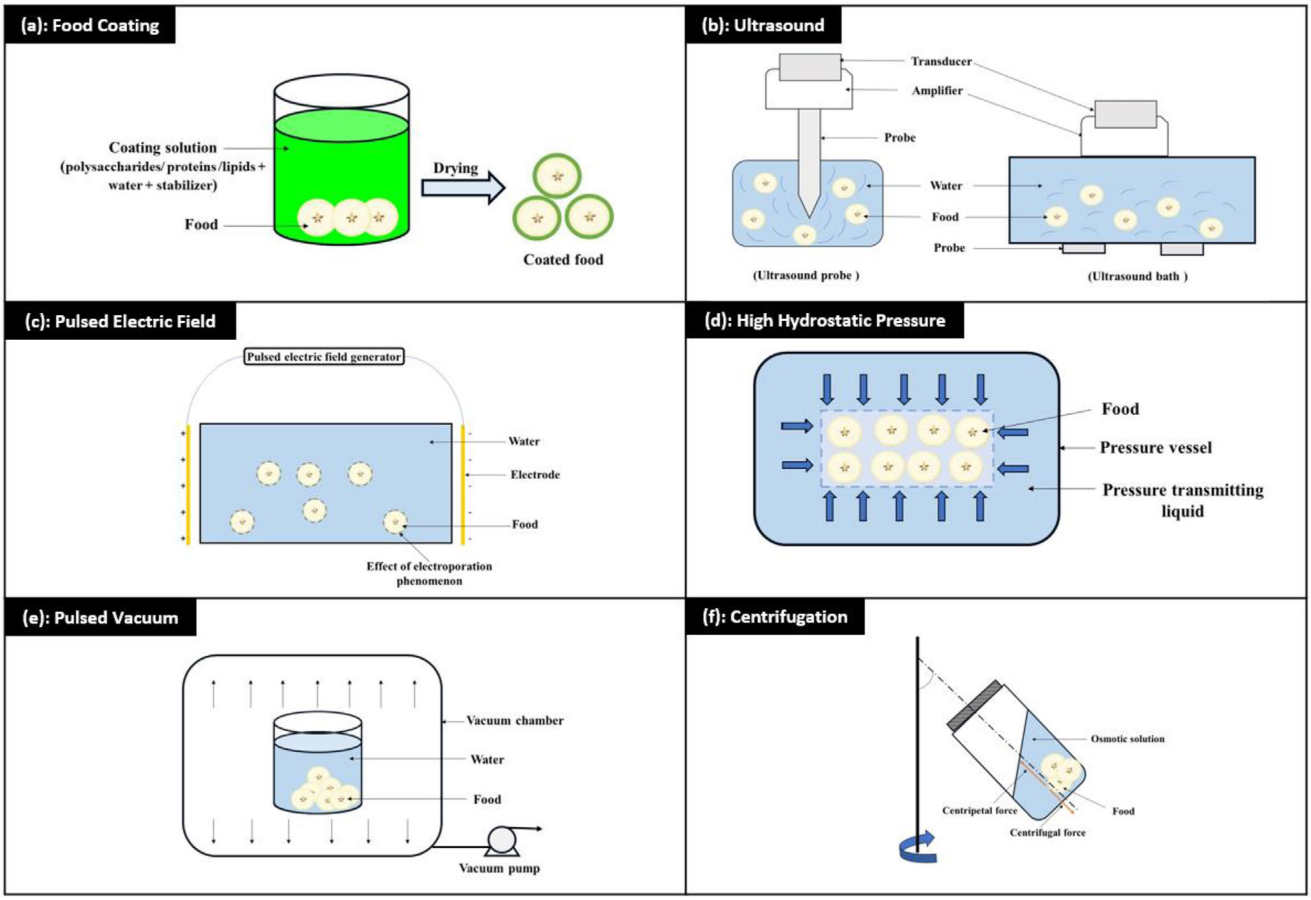


FIGURE 3 Illustration of various pretreatment technologies used before osmotic dehydration.

SG. In addition, PEF is typically carried out at ambient temperature, and many studies note a small increase in temperature (≤5–7°C) (Ade-Omowaye et al., 2002; Amami et al., 2014; Dermesonlouoglou et al., 2016). Therefore, PEF may be suitable for preserving nutrients, bioactive compounds, and the quality of food products.

5.5 | High hydrostatic pressure

HHP, a nonthermal technology, involves subjecting a material to high pressure (Figure 3d). Foods are prepackaged in polyethylene pouches and, along with osmotic solution, placed in a pressure chamber filled with a pressure transmission medium (Aghajanzadeh & Ziaiifar, 2021; González-Pérez et al., 2021), such as water and mixtures of ethanol, oil, and propylene glycol (Fayaz et al., 2022; González-Pérez et al., 2021; Rastogi & Niranjan, 1998). Pressure is applied uniformly, typically 100–800 MPa, at specific temperatures (Swami Hulle & Rao, 2016). Application of HHP leads to physical compression and mechanical volume reduction, which finally cause tissue permeabilization in various fruits and vegetables, resulting in higher rates of diffusion and dehydration (González-Pérez et al., 2021). There are key process parameters affecting HHP efficiency, including pressure, processing time, temperature, and food properties. The choice of process conditions is critical to safeguard product quality and minimize process cost. As shown in Table 3, the combination of HHP and OD improves mass transfer and the quality of the final product. For instance, the application of HHP (300–500 MPa) as a pretreatment for OD led to better preservation of the color and total phenolic content of strawberries (Nuñez-Mancilla et al., 2013). Verma et al. (2014) observed that the combination of HHP (100–500 MPa) and OD in sucrose solution increased both the WL and SG of bananas.

5.6 | Pulsed vacuum

In food products, gas is naturally trapped within the porous structure, creating barriers to WL, SG, and WR during OD. A pulsed vacuum is used to increase the internal surface area and volume of the porous product (Figure 3e). Pulsed vacuum OD (PVOD) temporarily reduces the operating pressure (~50–100 mbar), causing changes in the microstructure of the food and resulting in the release of entrapped gas (Fito et al., 2001). Once the pressure is restored to atmospheric levels, the product undergoes compression, and the entrapped gas is replaced by an osmotic solution (Fito et al., 2001). This expansion and compression phenomenon increases the occupation of the internal surface area by the osmotic solution, facilitating mass transfer and consequently improving the overall OD performance (Fito et al., 2001; Li & Ramaswamy, 2006). In PVOD, mass transfer is governed by a hydrodynamic mechanism (Fito et al., 2001), which leads to the diffusion of solutes through the plant membrane, driven by both pressure and concentration gradients. The flow of each solute component through the membrane is described by (Ibarz & Barbosa-Cánovas, 2002)

$$\vec{J_i} = -\frac{D_i\ C_\mathrm{i}}{\mathrm{RT}}\nabla\ \mu_i = -\frac{D_i\ C_\mathrm{i}}{\mathrm{RT}}\left(\frac{\partial \mu_i}{\partial C_i}\nabla C_i + \vec{V_i}\ \nabla P_i\right) \tag{12}$$

where $\vec{J_i}$ represents the flux of component i; D_i and C_i are the diffusion coefficient and concentration of component i in the membrane, respectively; μ_i represents the chemical potential; and $\vec{V_i}$ and P_i refer to the partial molar volume and applied pressure, respectively. As shown in Table 3, in most cases, both WL and SG were enhanced when the PVOD was used for cantaloupe, tomato, eggplant, apple, and pumpkin. However, SG was reported as minimal for eggplant and pumpkin by de Jesus Junqueira et al. (2017) and Corrêa et al. (2014), respectively. These findings suggest the potential application of pulsed vacuum to restrict the uptake of solids during OD.

5.7 | Centrifugal force

Centrifugation can improve the efficiency of OD by reducing the moisture content of foods without requiring a phase change in water. Therefore, combining centrifugal force with OD can lead to an increase in WL and a reduction in energy consumption. As depicted in Figure 3f, a centrifugal force employed during OD involves the application of a rotational speed to the sample-solution system (Amami et al., 2007). Few studies have evaluated the effect of the combination of centrifugal force and OD on food processing. Barman and Badwaik (2017) reported that the application of centrifugal force was more effective than the US in improving mass transfer during OD. Amami et al. (2007) investigated the effect of centrifugation on the OD of PEF-treated carrots and found that the application of both centrifugal force and PEF improved WL. In addition, centrifugal force diminishes SG during OD, resulting in the production of low-calorie osmotic dehydrated products.

5.8 | Microwave heating

Microwaves (MW) operate within the frequency range of 300 MHz to 300 GHz (Schiffmann, 2020). MW heating provides numerous advantages for processing food materials, such as enhanced energy efficiency and rapid heating (Manzoor et al., 2023). MW heating is known to be more economical compared to conventional heat treatments (Cinquanta et al., 2010). Dipole rotation and ionic polarization are the primary mechanisms involved in the MW heating of food products containing water and ionic compounds, respectively. During MW heating, polar molecules (like water) and ionic compounds (like salts) undergo continuous reorientation to align with the MW electric field. Heat is produced within the sample due to the friction, pushing, pulling, and collision of these molecules or ions as they undergo this continuous alternating reorganization (Ahmed, Ramaswamy, et al., 2016; Benlloch-Tinoco et al., 2013). As a result, MW heating can enhance mass transfer during OD and, in some cases, can also induce the formation of surface microcracks (Zielinska & Markowski, 2018). The application of MWs along with OD enhances mass transfer, leading to increased WL and reduced SG. Sharif et al. (2018) reported an increase in WL and the preservation of antioxidants and phenolic components in blueberries when MW-assisted OD was applied. Zielinska et al. (2018) observed an increase in WL and a slight effect on SG after MW vacuum OD treatment of cranberries. Kowalska et al. (2007) reported that under specific power and time conditions, MW treatment of apples improved both WL and SG during OD. Although these findings demonstrate the potential of MW applications, further research is needed to fully understand and optimize the benefits of combining MWs with OD in various food-processing applications.

5.9 | Ohmic heating

Ohmic heating (OH) is an electrothermal technology that heats food by utilizing its abundant ions to conduct electricity (Allali et al., 2010). During OH, an electrical current passes through food, positioned between two electrodes, to generate heat (Aghajanzadeh & Ziaiifar, 2018). Heat is rapidly generated by the electrical resistance of the food materials, making OH a high-temperature, short-time process (Allali et al., 2010; Mason et al., 2011). The permeabilization of cellular membranes occurs owing to both thermal effects and pore formation resulting from electroporation, which is a nonthermal phenomenon (Aghajanzadeh & Ziaiifar, 2018). During OH, the increase in temperature is influenced by electrical conductivity, particle size, ionic concentration, field strength, and the characteristics of the electrodes (Aghajanzadeh et al., 2023). Generally, the application of OD in combination with OH could be performed under atmospheric or vacuum conditions to increase the WL while preserving the quality of the final product (Allali et al., 2010). According to Aghajanzadeh and Ziaiifar (2018), OH allows rapid heating and even heat distribution and has a compact system design and high energy efficiency. However, the effectiveness of OH depends on several factors, including the electrical resistance of the food, holding time, intensity of the applied electrical field, and temperature (Ramaswamy et al., 2014). Moreno et al. (2017) investigated the effect of OH on polyphenol retention in apples after OD treatment and storage, revealing that the combination of OD with OH and pulsed vacuum resulted in better polyphenol retention than that observed in the control without OH. Kutlu (2022) demonstrated that the application of OH during OD led to an improvement in the phenolic content, rehydration ratio, color, and dielectric properties of quince compared with those of untreated quince. These findings demonstrate the potential of OH to enhance food processing and product quality across various applications.

5.10 | Gamma irradiation

Gamma irradiation at doses not exceeding 10 kGy is safe, according to the Food and Agriculture Organization (FAO) (Rastogi, 2005). Gamma irradiation induces alterations and injuries in the internal tissue structure of foods, leading to membrane permeabilization of plant cells and facilitating improved mass transfer during OD (Ahmed, Qazi, et al., 2016). Indeed, the combined approach of irradiation and OD reduces the necessity for thermal treatments, effectively preserving the quality and nutritional value of the final product (Ramya & Jain, 2017). Rastogi (2005) and Rastogi and Raghavarao (2004) observed enhanced mass transfer facilitated by gamma irradiation during OD, leading to increased WL and SG in carrots and potatoes, respectively. However, limited research has comprehensively examined the effect of gamma irradiation as a pretreatment for OD.

5.11 | Supercritical carbon dioxide

Supercritical carbon dioxide ($SCCO_2$) is a rare OD pretreatment and is considered a green technology because it does not require toxic chemical solvents. The application of $SCCO_2$ presents numerous advantages, such as being odorless, colorless, chemical-free, safe, and preventing undesired oxidation reactions during food processing (Aghajanzadeh et al., 2023). In addition, CO_2 has a moderate supercritical condition (31.1°C, 73.7 atm), which makes it a suitable choice even for the drying of heat-sensitive products. Contact with $SCCO_2$ disrupts the lignocellulosic structure of fruits and vegetables, leading to membrane permeabilization and increasing the mass transfer during OD (Putrino et al., 2020). For instance, the pretreatment of mangoes with $SCCO_2$ resulted in an increase in SG during OD (Tedjo et al., 2002). According to Li and Ramaswamy (2005), treatment with supercritical carbon dioxide cannot enhance WL, but it may promote SG. The $SCCO_2$ shows that the uptake of solids during OD may not only be related to the permeabilized cells but could also be influenced by the nature of chemical and structural changes induced by the pretreatment. By manipulating pressure and temperature as process variables, it becomes possible to adjust the solvent power of the medium within specified ranges as needed, eliminating the necessity to alter the solvent's composition (Tedjo et al., 2002).

5.12 | Skin treatments

Some fruits and vegetables have thick waxy skins that limit WL and SG and extend the duration of OD (Shi et al., 1997) (Table 3). In the case of Roma tomatoes, OD can take up to 60 h, owing to the resistance of the skin to mass transfer (Tsamo et al., 2005). Prolonged dehydration can adversely affect the quality of the final product (Shi et al., 1997). Cranberries, distinguished by their waxy and thick skins, are susceptible to swelling, bursting, and leakage during OD if not subjected to proper pretreatment (Beaudry et al., 2000). To address the issues regarding skin resistance during OD, various chemical, mechanical, and thermal pretreatments have been tested.

5.12.1 | Chemical pretreatments

During chemical pretreatments, whole fruits and vegetables are exposed to an alkaline or acidic solution of oleate esters for a few minutes to remove the waxy layer from the skin and reduce its thickness (Sunjka & Raghavan, 2004). Immersing the product in oleate esters helps to dissociate the surface wax (Venkatachalapathy, 1998), and alkaline solutions create small pores as they penetrate the fruit skin by dissolving the waxy layer (Di Matteo et al., 2000). Shi et al. (1997) observed that pretreatment of tomatoes with a combination of NaOH and ethyl oleate prior to OD resulted in less damage to the peel and higher WL than that using NaOH alone. Chemical pretreatment of cranberries using a solution of ethyl oleate (2%) and NaOH (0.5%) showed limited impact on mass transfer, likely because of the short pretreatment time (1–3 min) (Sunjka & Raghavan, 2004). It should be noted that higher concentrations of the solution were found to affect the product quality by dissolving cell wall polysaccharides and causing softening. Therefore, considering the specific properties of the product and the processing conditions, the selection of the appropriate type and concentration of solution in the chemical pretreatment is important for enhancing the efficiency of OD while preserving the quality of the product.

5.12.2 | Mechanical pretreatments

Mechanical pretreatments, such as cutting, puncturing, or abrasion of the skin, are effective in enhancing OD by exposing the interior parts of fruits and vegetables to osmotic solutions and facilitating mass transfer (Sunjka & Raghavan, 2004). Cutting cranberries into halves and quarters (Sunjka & Raghavan, 2004) or puncturing tomato skin with needles (Shi et al., 1997) results in higher mass transfer than chemical pretreatments, mainly because of the increased surface area available for OD. Another advantage of mechanical treatment is the reduced risk of chemical components being introduced into the flesh of fruits and vegetables, making the treated produce more acceptable to consumers.

5.12.3 | Thermal pretreatments

High temperatures can be employed through pretreatment using boiling or steam blanching to facilitate the peeling of fruits and vegetables (Araya-Farias et al., 2014). However, high temperatures can potentially damage the tissue of fruits and vegetables, leading to the leaching of soluble solids into the osmotic solution. To address this, cold pretreatment with liquid nitrogen (−196°C) is used in the processing of blueberry skins (Ketata et al., 2013). Cryogenic pretreatment involves one to three immersion-thawing cycles of 8 and 10 s for lowbush and highbush blueberries, respectively. Cryogenic pretreatment accelerates mass transfer by decreasing the cuticle thickness and wax content, leading to reduced shrinkage during OD. However, a decrease in the anthocyanin content of lowbush blueberries was observed as they were dissolved in the osmotic solution after the removal of the wax layer (Ketata et al., 2013). Adjusting the number of immersion-thawing cycles may help mitigate the negative effects of cryogenic pretreatment on food properties.

6 | PROCESS INTENSIFICATION

Process intensification is a concept denoting any advancement that leads to sustainable process, compact equipment, and efficient technologies (Satyawali et al., 2017). Figure 4 depicts the main principles of process intensification and its expected benefits in OD. Feng et al. (2019) utilized a combined approach of vacuum and US to produce high-quality garlic using OD. Rastogi (2005) and Rastogi and Raghavarao (2004) observed enhanced mass transfer facilitated by gamma irradiation during OD, leading to increased WL and SG in carrots and potatoes, respectively. Zielinska et al. (2018) used MW vacuum pretreatment to process cranberries, resulting in modifications in the resistance of the external layers and improvements in WL and SG. However, Dellarosa et al. (2017) observed an antagonistic effect on drip loss when PEF and US were combined as a pretreatment for mushroom stalks. This was attributed to the intense effect of heating on cell disruption and changes in the solution properties caused by US cavitation. Therefore, careful consideration is essential when choosing the technologies and conditions for specific combinations to avoid possible antagonistic effects.

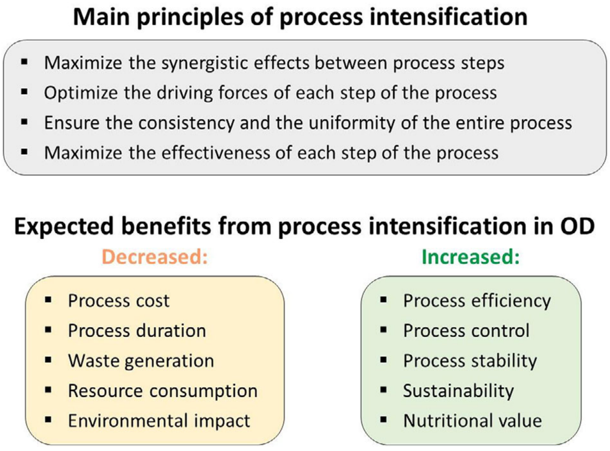


FIGURE 4 Main principles of process intensification and its expected benefits in osmotic dehydration.

7 | OPPORTUNITIES AND CHALLENGES IN OSMOTIC DEHYDRATION

7.1 | Food waste valorization

Waste produced during food processing is typically discarded in landfills, used to produce compost, or repurposed as animal feed (Aghajanzadeh et al., 2023). However, these wastes contain valuable components, such as proteins, vitamins, and minerals. One strategy for tackling food waste issues and enhancing financial returns is to use this waste in the OD process to produce functional foods and high-value ingredients. For example, strained yogurt whey was used in the OD of pumpkins for solid enrichment and improved SG to produce high-quality snacks (Dermesonlouoglou et al., 2020). Recently, Soleimanian et al. (2023) demonstrated the potential of combining two food waste streams to produce innovative products. They transformed discarded tomatoes into high-value-added products, including tomato sauce, nectars, pastes, and powders, when using whey as an osmotic solution. In some cases, the application of food waste as an osmotic solution can be challenging because of its lack of solubility or compatibility with the desired final product. Hence, preliminary studies are required to determine the appropriate synergies between the food waste streams before scaling up the process. Additionally, an assessment of the overall product quality according to consumer acceptance criteria should be carried out at an early stage of the process.

7.2 | Reuse management of the osmotic solution

The industrial scale of OD results in the generation of a significant amount of osmotic solution, which contains dissolved sugars, salts, and other solutes, including valuable vitamins and antioxidants. In the context of sustainability, recycling ingredients, reuse of the osmotic solutions, and waste disposal in general are critical aspects in the food industry (Pandiselvam et al., 2022). Hence, effective waste management strategies are imperative for mitigating environmental impacts and making processes more economical (Osorio et al., 2007). For instance, the osmotic solution used in the OD of pineapples can be applied to the production of fermented beverages using kefir grains (Maldonado et al., 2020) or fruit dragée (Germer et al., 2017). Furthermore, osmotic solutions can enhance the nutritional value of animal feed. Therefore, by developing a cross-industry osmotic-solution recycling network, businesses can significantly decrease their adverse environmental impacts and maintain economic growth by efficiently employing this valuable resource.

7.3 | Reducing energy consumption

Drying technologies require high-energy inputs to provide the latent heat required for water evaporation. Furthermore, during drying, such as air drying, there is the potential for waste of thermal energy, leading to excessive energy consumption and high process costs (Motevali et al., 2011). Unlike drying, OD achieves water extraction without undergoing a phase change, thereby eliminating the need for latent heat. OD is conducted at relatively mild temperatures (<50°C), resulting in energy savings. Filipović et al. (2019) reported heat energy savings of up to 1825.66 kJ/kg when using OD as a pretreatment for chicken meat before air-drying. Furthermore, during OD, the uptake of solutes lowers water activity, which enhances the efficiency of the subsequent drying steps and reduces the drying time and overall energy consumption. These factors are crucial from both technological and industrial perspectives, resulting in reduced production costs. To achieve this goal, it is essential to select appropriate OD processing conditions, osmotic solutions, and pretreatment technologies.

7.4 | Infusion of bioactive components

In response to the growing consumer demand for functional and healthy food options, OD has undergone innovations to create food products infused with a variety of minerals and bioactive components, such as inulin (Jiménez-Hernández et al., 2017), calcium (Macedo et al., 2023; Silva et al., 2014), vitamins and antioxidants (polyphenols, anthocyanins, and ascorbic acid) (Kowalska et al., 2023; Kowalska et al., 2020), and prebiotics. These bioactive components are often combined with sugars derived from fruit juice concentrates or natural syrups sourced from plants known for their health-promoting properties. For instance, chokeberry juice concentrate is effectively used to increase the content of ascorbic acid, polyphenols, and antioxidants in fruits and vegetables, enhancing their color attributes and organoleptic qualities (Kowalska et al., 2020; Masztalerz et al., 2021; Samborska et al., 2019). Considering the advantages of process intensification (Figure 4), it can constitute an efficient approach for infusing bioactive components such as those produced by probiotics during OD. Therefore, the incorporation of bioactive components into osmotic solutions demonstrates the potential of OD to improve the nutritional profile and quality of food products. Nonetheless, it is crucial to carefully manage the flavor of a product to ensure its acceptance by consumers, striking a balance between health benefits and taste.

7.5 | Simple mathematical models for mass transfer predictions

In OD, Fick's law is commonly used to predict mass transfer kinetics and diffusion coefficients, assuming that mass transfer occurs purely through diffusion and that any external resistance is negligible. However, as discussed in Section 4.3, external mass transfer can become a dominant factor, especially for viscous solutions (Zongo et al., 2023), and mass transfer can also be dictated simultaneously by both internal and external mechanisms. In these special contexts, using Fick's law is not appropriate; therefore, other alternatives should be explored without suggesting complex mathematical expressions. (Nguyen et al., 2023) developed a very simple model that can be used for predicting dehydration kinetics, which includes both internal and external heat resistances. One suggestion is to investigate the possible adaptation of this type of convenient and practical model, developed for heat transfer, to the mass transfer that occurs during OD.

8 | CONCLUSIONS

OD is an effective technology for removing a substantial quantity of water from the food without any phase changes, resulting in reduced energy consumption. This review provides insights into OD by reviewing its principles, critical factors, kinetics, and advancements. One of the most important phenomena in OD is the mass transfer exchange between the food and the hypertonic solution, driven by the chemical potential gradient. Several factors influence the effectiveness of the OD process, including the properties of the food product and osmotic solution, as well as the process conditions. To achieve the desired dehydration rates, various models have been suggested for studying OD kinetics. This review highlights the potential of promising technologies for enhancing OD, such as coating, freezing/defrosting, US, PEF, HHP, centrifugation, and skin treatments. New opportunities for the use of OD in the food industry are also presented, including the incorporation of bioactive components into foods through OD, which has opened a new era in the production of functional foods. Reutilization of osmotic solutions to produce new food products is an effective way to reduce waste. Additionally, exploring the possible synergy between different food waste streams could lead to an elegant approach for mitigating the environmental impacts of some industries. In conclusion, OD is a promising technology that requires some fine-tuning to make it more attractive at industrial scale. Indeed, further investigations, including (i) switching the process of OD from batch to continuous, (ii) cleaning-in-place of the OD process equipment, (iii) assessing the microbiological evolution of the osmotic solutions intended for reuse, (iv) gathering reliable data of the world market of OD, and (v) evaluating the economic feasibility of OD at industrial scale, are still needed.

AUTHOR CONTRIBUTIONS

Ali Asghari: Validation; writing—original draft; visualization; writing—review and editing. **P. Assana Zongo**: Writing—original draft; writing—review and editing; validation; visualization. **Emmanuel Freddy Osse**: Visualization; validation. **Sara Aghajanzadeh**: Writing—review and editing; methodology; visualization; validation; writing—original draft. **Vijaya Raghavan**: Writing—review and editing. **Seddik Khalloufi**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing; visualization; validation; methodology; resources; supervision; project administration.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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