TRANSACTIONS ON SCIENCE AND TECHNOLOGY

Osmotic dehydration with blanching, pulsed electric fields, and ultrasound: A mini-review

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ABSTRACT Osmotic dehydration (OD) has emerged as a valuable food preservation technique that extends shelf life and retains nutritional value by partially removing water from food through immersion in a hypertonic solution. However, conventional OD faces challenges, including slow mass transfer rates, long processing times, and potentially degrading sensory and nutritional qualities. This mini-review explores the role of blanching, pulsed electric fields (PEF), and ultrasound as pre-treatment methods to enhance the efficiency of OD. Blanching, a traditional thermal technique, effectively prepares food for OD by inactivating enzymes and altering structural properties, although it may lead to nutrient loss. Non-thermal methods like PEF and ultrasound offer significant advantages, including increased cell permeability, faster dehydration, and improved product quality. These methods accelerate the OD process and reduce energy consumption, making food processing more cost-effective and environmentally sustainable. The review highlights the importance of selecting appropriate pre-treatment methods to optimize OD, leading to higher quality and more marketable food products. Future research should focus on optimizing these techniques and exploring combined pre-treatment methods to further enhance the effectiveness and sustainability of osmotic dehydration. The pre-treatments not only improve process efficiency but also facilitate scalability, enabling wider implementation in the food industry.

KEYWORDS: Osmotic dehydration; Pre-treatment; Blanching, Pulsed electric field; Ultrasound
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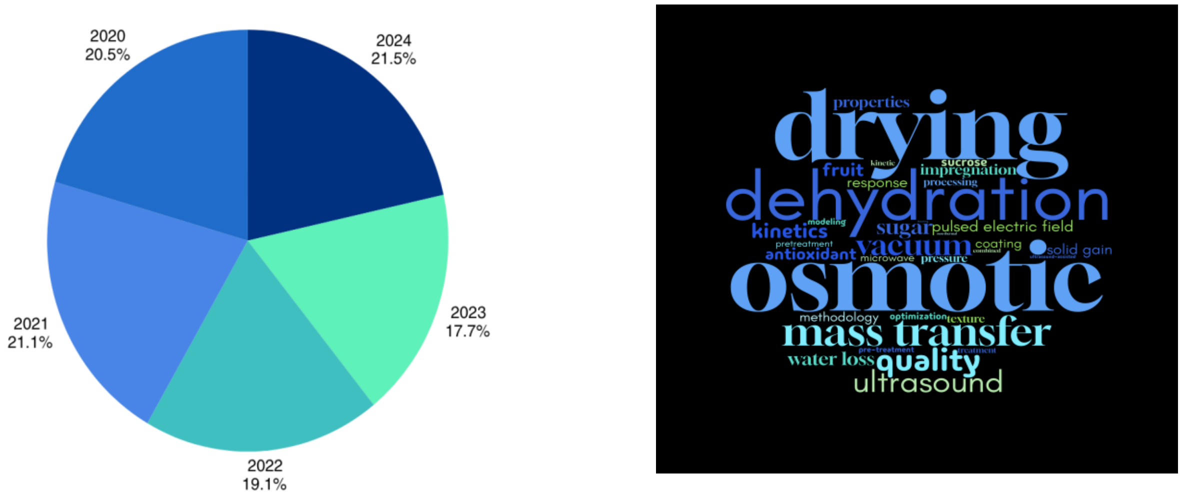
Review Article

INTRODUCTION

Food preservation is critical to ensuring food safety, extending shelf life, and maintaining nutritional value. One of the key methods of food preservation is drying. Conventional drying techniques such as hot air drying, freeze drying, and spray drying, often come with challenges such as high energy consumption, long processing times, and potential degradation of nutritional and sensory qualities (Nwankwo *et al.*, 2023; Zare *et al.*, 2024). Thus, osmotic dehydration (OD) has emerged as a valuable pre-treatment technique in food drying and preservation, offering significant energy savings and quality improvements (Rastogi, 2023). The scientific exploration and formal application of OD began in the 20th century with advancements in food technology. Every year, a significant amount of research is actively conducted on OD. Figure 1(a) presents an overview of the 397 articles published between 2020 and 2024 on OD in the subject area of agricultural and biological sciences, obtained from the Scopus database. This continuous effort highlights the scientific community's interest in understanding and improving this process. Figure 1(b) presents a keyword cloud showcasing the most prominent keywords that reflect key research focuses on the OD process, covering topics such as drying kinetics, pretreatment methods, and quality preservation.

OD is a process of partial water removal from food by immersing it in a hypertonic solution. Through the principles of osmosis and diffusion, water molecules from the food move to a hypertonic solution, and the solutes from the solution diffuse into the food. These two major mass transfer processes are commonly known as water loss (WL) and solute gain (SG), and occur concurrently. With the rising demand for low-sugar and low-salt foods, minimizing the SG is increasingly important to align with health-driven market expectations while maintaining effective WL performance (Asghari *et al.*, 2024; Park *et al.*, 2020). While bioactive compounds present in the food may leach out into the surrounding solution during osmotic dehydration, potentially affecting the nutritional and sensory quality of the final product, this loss can be minimized and effectively controlled by optimizing the dehydration process (Solgi *et al*., 2021). From economic point of view, this partial dehydration process, which involves no phase change, can significantly reduce drying time and energy requirements when combined with conventional drying methods (Malakar *et al*., 2021).



(a) (b)

Figure 1. Publication database from 2020 to 2024 on osmotic dehydration. (a) Article distribution. (b) Most cited keyword cloud.

Researchers are exploring various aspects of OD, including the optimization of pre-treatment techniques, enhancement of efficiency, and evaluation of effects on nutritional and sensory qualities. In this context, the role of pre-treatment in OD is of great interest. This mini-review explores the crucial role of pre-treatment in OD, with a focus on blanching as a conventional method and the emerging techniques of pulsed electric fields (PEF) and ultrasound. It highlights how these methods enhance mass transfer rates, reduce drying time, and significantly improve the overall quality of dried products.

ROLE OF PRE-TREATMENT IN OSMOTIC DEHYDRATION

In the conventional OD process, the slow nature of mass transfer leads to a time-consuming process. This is particularly evident when OD is employed as an infusion technique, where the process can extend over several weeks (Selvi *et al*., 2014). Furthermore, excessive solute during OD process can lead to undesirable sensory attributes, such an overly sweet or salty product, which can negatively impact consumer acceptance (Lazarides, 2019). Moreover, high solute concentration also poses health concerns, as it may increase the sugar or salt content of the food, making it less suitable for health-conscious consumers (Khan Ahmadzadeh, 2021). Additionally, the excessive infusion of solutes can lead to structural changes that make the food less appealing, such as increased hardness or loss of natural juiciness. These drawbacks highlight the need for pre-treatment techniques to be significantly improved through various methods ultimately enhancing the dehydration rate and product quality.

One of the key outcomes that can be achieved through pre-treatment is the enhancement of cell membrane permeability, which facilitates the formation of pores. These structural modifications increase the surface area, allowing for more efficient mass transfer (Bai *et al*., 2023; Hissham *et al*., 2023). Consequently, the dehydration process becomes faster and more effective, reducing the total drying time. This reduction not only boosts productivity but also minimizes food exposure to prolonged heat, helping to preserve and enhance the nutritional and sensory qualities of the food, which are crucial for consumer acceptance and marketability.

Moreover, the reduction in drying time achieved through effective pre-treatment methods is directly linked to lower energy consumption, making dehydration more cost-effective and environmentally sustainable. In large-scale food processing, where energy costs are substantial, improving energy efficiency is essential for lowering operational expenses and the environmental footprint (Menon *et al.*, 2020). By selecting the appropriate pre-treatment method, food processors can enhance OD efficiency, leading to better product quality, reduced processing times, and a sustainable production process. This ensures that food products retain desirable qualities and appeal to health-conscious consumers while minimizing energy costs and environmental impact.

PRE-TREATMENT TECHNIQUES IN OSMOTIC DEHYDRATION

Conventional pre-treatment techniques in food processing, such as blanching, are widely used to enhance the efficiency of dehydration processes. However, non-thermal pre-treatments, including pulsed electric field (PEF) and ultrasound, are gaining increasing attention for their ability to significantly enhance mass transfer rates during dehydration without the need of thermal methods. Detailed discussions of blanching, pulsed electric field (PEF), and ultrasound are as follows:

Blanching

Blanching is a traditional pre-treatment technique commonly used in food processing, especially before dehydration. This process involves briefly exposing fruits or vegetables to boiling water or steam, followed by rapid cooling in ice water to halt the cooking process (Liceaga, 2021). This method inactivates enzymes that can cause spoilage, enhance colour retention, and soften the tissue, making the food more amenable to subsequent dehydration processes like OD. While blanching can result in some nutrient loss, especially of heat-sensitive vitamins like vitamin C (Lagnika *et al.*, 2021), it remains popular due to its simplicity and effectiveness in preparing foods for advanced dehydration techniques. Shorter blanching times and lower temperatures generally result in better nutrient retention. Recently, Mugo *et al.* (2024) reported that blanching kale for 15.2 minutes at 80°C and spinach for 17.7 minutes at 84°C resulted in higher retention of vitamins B1, B3, and C compared to longer blanching durations. Nevertheless, optimizing blanching parameters such as time, temperature, and method can help minimize these losses.

Putsakum *et al.* (2020) examined the effects of various blanching periods and immersion in sodium metabisulfite/citric acid solution on nutmeg pericarp. The study found that longer blanching periods reduced texture hardness, myristicin content, and enzyme activity. Specifically, a seven-minute blanching period was optimal, reducing myristicin to undetectable levels and lowering enzyme activity, resulting in a safer pickled nutmeg product. Similarly, (Jagannath & Kumar, 2016) examined debittering and storage losses of naringin, a natural flavonoid in oranges subjected to OD. The research found that blanching at mild temperatures followed by OD reduced naringin content, making the product more acceptable by reducing bitterness and maintaining quality during extended storage. These studies illustrate how careful control of blanching conditions can optimize the effectiveness of the dehydration process while ensuring product safety and quality.

Garcia *et al.* (2021) investigated the impact of blanching on OD in papaya and reported that blanching not only improves WL and SG by altering the structural properties of the fruit but also aids in the extraction of enzymes like invertase, which further enhances the dehydration process. By softening cell walls and inactivating enzymes that cause spoilage, blanching enables more uniform and rapid moisture removal during OD. Additionally, a study by Dhiman *et al.* (2022) demonstrated that mulberries pre-treated with a 170-second blanching time, followed by OD and further drying in a tray dryer, retained better nutritional and phytochemical properties while maintaining their original shape. These findings highlight the importance of selecting appropriate blanching conditions to optimize the OD process, ensuring the final product retains its desired sensory and nutritional characteristics.

Pulsed Electric Field (PEF)

PEF treatment involves the application of short bursts of high-voltage electric pulses to food products, leading to the formation of pores in cell membranes and increasing cell permeability. This non-thermal process, known as electroporation, involves the application of high-voltage electric pulses typically ranging from 20 to 80 kV/cm for a very short duration, usually between 1–100 μs (El Kantar & Koubaa, 2022). This process induces the formation of pores in the cell membranes, which can lead to the disruption of cellular structures, making it a useful technique for processing various types of foods, including liquid, semi-liquid, and solid forms.

The parameters of PEF treatment, such as field strength and pulse number, are critical factors that significantly influence mass transfer during osmotic dehydration. Higher field strengths and a greater number of pulses have been shown to enhance both water loss and solid gain during the process of osmotic dehydration. This is because increased field strength and pulse number lead to more extensive cell membrane disruption, which facilitates the movement of water out of the cells and the uptake of solutes into the cells. Studies by Nazari *et al.* (2019) confirm these findings, demonstrating that optimizing these parameters can improve the efficiency of osmotic dehydration in various food processing applications.

PEF treatment has been shown to reduce energy consumption in drying processes by acting as an effective pre-treatment. Research conducted by Paraskevopoulou *et al.* (2022) demonstrated that the combined use of PEF and osmotic dehydration as pre-treatments before air-drying can lead to a significant reduction in processing time by up to 27% and a corresponding energy reduction of 50% in the drying of pumpkin. Similarly, Dermesonlouoglou *et al.* (2018) reported that applying PEF of 2.8 kV/cm with 750 pulses combined with osmotic dehydration prior to air drying reduced the processing time by 33% while also improving colour retention, antioxidant capacity, and total phenolic content in goji berries. These findings clearly illustrate the potential of integrating PEF and osmotic dehydration in food processing to achieve more efficient and sustainable drying processes while maintaining or even enhancing the nutritional and sensory qualities of the products.

Recently, a study by Liu *et al.* (2023) reported that combining PEF with blanching reduces moisture and oil content in products like sweet potato chips, improving texture and reducing undesirable compounds such as acrylamide. Previously, Zhang *et al.* (2021) also reported that French fries obtained through the combined pretreatment showed improved physiochemical properties and a better food safety profile, with a lower colony count and acrylamide content, offering a practical approach for healthier and tastier fried potato products. The combined PEF-blanching pretreatment could thus serve as a potential pretreatment method for osmotic dehydration, enhancing moisture removal, improving texture, and facilitating a more efficient dehydration process.

Ultrasound

Ultrasound, a novel non-thermal process, is being widely recognized for its role as a pre-treatment in enhancing the efficiency of osmotic dehydration. The application of high-frequency sound waves typically in the range of 20 kHz to 100 kHz is used (Karizaki, 2020). Ultrasonic waves generate cavitation bubbles within the liquid medium surrounding the food material. When these bubbles collapse, they produce micro-jets and localized high temperatures and pressures, which disrupt the cellular structure of the food material (Zhou *et al.*, 2024). This disruption increases the permeability of cell membranes, facilitating the faster removal of water and the uptake of osmotic agents like sugars or salts. As a result, the mass transfer rate during the osmotic dehydration process is significantly enhanced.

Mehta *et al.* (2021) investigated the ultrasonic-induced effects on the mass transfer characteristics of aonla slices during osmotic dehydration. The study demonstrated significant improvements in WL and SG, which enhanced dehydration efficiency. Similarly, Xu *et al.* (2022) examined the use of multi-frequency power ultrasound in the intermediate-wave infrared drying of pineapple slices. The findings revealed that ultrasonic pre-treatment increased drying efficiency and improved quality attributes, such as colour retention and texture. Further studies, such as those by Basumatary *et al.* (2024), demonstrated the impact of different ultrasound conditions on osmotically dehydrated carrots. The research showed that varying ultrasonic power and exposure time could optimize the balance between WL and SG, resulting in improved product quality. Bozkir and Ergün (2020) also investigated the combined effects of sonication and osmotic dehydration on persimmons, revealing improvements in drying kinetics and product quality. Salehi *et al.* (2022) focused on the influence of sonication power and time on banana slices, finding that ultrasonic pre-treatment significantly enhanced the osmotic dehydration process efficiency, reducing the time required and improving the overall quality of the dehydrated bananas.

A study by Wu *et al.* (2020) reported that the combined blanching and ultrasound-assisted osmotic dehydration pretreatment significantly improved drying efficiency, enhanced water mobility, reduced drying time, and preserved the green colour and rehydration ratio of dried Pakchoi stems. A combined pretreatment using PEF and ultrasound has been carried by Pobiega *et al.* (2023) on strawberries, showing enhanced mass transfer during osmotic dehydration. Although reductions in bioactive compounds such as polyphenols, anthocyanins, and vitamin C were observed, their levels remained comparable to conventionally osmotically dehydrated samples. Previously, Nowacka *et al.* (2017) found that while ultrasound alone has little impact on the thermal and mechanical properties of cranberries, its combination with blanching enhances the efficiency of heat and mass transfer, leading to more significant changes in tissue structure and dehydration efficiency. further showed that adding PEF into the combination amplifies these effects, resulting in cranberries with higher anthocyanin and flavonoid content, reduced sugar uptake and a drying time shortened by up to 55% compared to cutting alone. This trio of pretreatments overcomes the limitations of individual methods by enhancing dehydration efficiency while preserving nutritional quality, making it a promising method for food processing.

Comparison of Pre-treatment Techniques

Blanching, pulse electric field (PEF) and ultrasound possess their own mechanisms in enhancing the OD process. Meanwhile, the combination of non-thermal and thermal processing techniques in food treatment has emerged as a promising pretreatment strategy to enhance food quality, safety, and shelf life (Kaur *et al.*, 2025). Table 1 presents a comparative summary of the pros and cons of each method and their combinations in the OD process, along with the best food types suited for each method. This will provide a clear overview of these innovative processing techniques.

Table 1: Comparative summary of pre-treatment methods for osmotic dehydration.

Method	Pros	Cons	Best Food Types	References
Blanching	- Simple process - Enhances OD mass transfer - Inactivates spoilage enzymes - Softens tissue	- Nutrient loss (heat-sensitive compounds) - May lead to texture changes (prolong blanching)	Hard skin vegetables or high enzyme activity (e.g., kale, spinach)	Garcia *et al.* (2021), Bai *et al.* (2023), Mugo *et al.* (2024)
PEF	- Enhances OD mass transfer - Nutrient retention - Reduces dehydration time	- Expensive equipment - Requires technical expertise - Safety concern	Soft fruits and vegetables; high-moisture foods (e.g., apples, pumpkins, strawberries)	Minming *et al.* (2023), Razola-Díaz *et al.* (2023), Paraskevopoulou *et al.* (2022)
Ultrasound	- Energy-efficient - Enhances OD mass transfer - Nutrient retention - Improves texture - Reduces drying time	- Limited effect when used alone - Nutrient loss at high intensity - Requires precise control of ultrasound parameters	Fruits and vegetables requiring mild processing (e.g., persimmons, bananas, carrots)	Basumatary *et al.* (2024), Salehi *et al.* (2022), Bozkir and Ergün (2020)
Blanching + PEF	- Enhances OD mass transfer - Nutrient retention - Reduces drying time	- Risk of thermal degradation - Requires process optimization	Root vegetables (e.g., potatoes, sweet potatoes)	Liu *et al.* (2023), Zhang *et al.* (2021)
Blanching + Ultrasound	- Improves colour and texture - Minimizes blanching time and nutrient loss	- Possible texture softening - Risk of thermal degradation - Requires precise control of ultrasound parameters	Fruits (e.g., kiwifruit, blueberries, cranberries), vegetables (e.g., Pakchoi stems)	Shujuan *et al.* (2025), Yu *et al.* (2024), Wu *et al.* (2020)
PEF + Ultrasound	- Non-thermal synergy - Improves OD mass transfer efficiency - Acceptable nutrient retention	- Some loss of bioactive components - High cost & technical complexity - Requires process optimization	Heat-sensitive fruits and vegetables	Pobiega *et al.* (2023)
Blanching + PEF + Ultrasound	- Enhanced OD mass transfer efficiency - Reduces drying time - Better retention of key bioactive compounds	- Partial loss of sensitive bioactive components - Expensive and complex setup - Requires precise parameter control & optimization	Nutritionally sensitive fruits and vegetables	Wiktor *et al.* (2019)

CONCLUSION

While this pre-treatment offers proven benefits, the main challenge lies in balancing the reduction of undesirable components (e.g., bitterness, enzyme activity) with the preservation of nutritional quality. Future research could focus on optimizing processing parameters to minimize nutrient loss while maximizing the efficiency of subsequent dehydration processes. Additionally, exploring combined treatments could further enhance the preservation of sensitive compounds while still achieving the desired textural and safety outcomes. This approach can be particularly beneficial for hard-to-dehydrate food materials. Furthermore, future studies should also aim to quantify the energy performance of non-thermal pretreatments (e.g., kWh/kg), which is critical for assessing their environmental sustainability and industrial scalability. Investigating these combined or alternative pre-treatment methods could significantly improve both the efficiency and quality of dehydration processes, particularly for nutritionally sensitive products.

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