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REVIEW ARTICLE

Food fortification potential of osmotic dehydration and the impact of osmo-combined techniques on bioactive component saturation in fruits and vegetables

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Abstract

Osmotic dehydration (OD) is a widely used technique for lowering the moisture content and water activity of biological products. During OD, food is immersed in an aqueous hypertonic solution of salt and/or sugar. Food and the surrounding osmotic solution have different osmotic pressures which allows for the transportation of solute from the osmotic solution into the food product. OD could be utilized as a fortification method by addition of solutes of interest to the osmotic solution. Adding vitamins, dietary fibers, and minerals (such as calcium, iron, and zinc) to the osmotic solution can be used to create food with specific health-promoting qualities. Fortification of fruit and vegetable goods would effectively minimize and prevent diseases linked to nutritional inadequacies due to the high consumption rate of these products. OD could be a simple, affordable, and effective way to fortify food for social, economic, and health benefits. This study compiles data from existing studies dating back approximately two decades, focusing on the possibility of adding or impregnating bioactive compounds into fruits and vegetables through OD as well as the effects of combining OD with vacuum, ultrasound, and pulse electric field techniques on the incorporation of these bioactive compounds into solid food matrices. A brief overview of current OD trends is also provided, highlighting the use of lower-calorie sugar replacements to improve process efficiency and raise overall product quality. This study emphasizes the need for more research into OD to fortify, improve functionality, and incorporate nutraceutical characteristics in the food industry.

Keywords: Ultrasound; Vacuum; Osmotic enrichment; Vitamins; Minerals; Osmotic solution.

Highlights

- The addition of essential vitamins, dietary fibers, and minerals to the osmotic solution can be an effective approach for producing fortified food products with enhanced nutritional value
- The fortification of fruits and vegetables can be an effective strategy to prevent diseases associated with nutritional deficiencies
- The exploration of diverse techniques, including vacuum treatment, ultrasound, and pulse electric field-assisted osmo-impregnation, suggests a promising potential for elevating the bioavailability and functional characteristics of food products

1 Introduction

Food fortification is the practice of improving the nutritional content of frequently consumed foods through the incorporation of vitamins and minerals during the processing stage (Asare et al., 2022). In recent years, food researchers have focused on the creation of functional or nutraceutical foods, driven by the increasing consumer awareness of the health benefits and disease-prevention properties associated with certain foods (Tylewicz et al., 2020). Functional ingredients include a range of components, comprising vitamins, minerals, antioxidants, probiotics, and prebiotics. These elements can be either found naturally in food or be introduced through fortification (Bellary et al., 2011). Functional foods, in addition to their nutritional benefits, have the capacity to aid in the treatment or prevention of one or more diseases. For instance, they may contribute to the reduction of blood pressure, cholesterol, and blood sugar levels, as well as lessen the risks associated with heart disease, cancer, and osteoporosis (Saydam et al., 2019).

Consumers are showing a keen interest in healthier food options due to their increased awareness and growing concern for their health and overall well-being (Tylewicz et al., 2020). Among the spectrum of health-conscious dietary options, fruits stand out due to their substantial nutrient profile, encompassing elements such as fiber, vitamins, minerals, and antioxidants (Basu et al., 2014). Functional foods can be developed by incorporating minerals, vitamins, or other bioactive components into these food products (Fito et al., 2001). Osmotic drying has proven effective in enhancing food quality. It involves the migration of water molecules from the food into an osmotically active solution, while solutes from the solution penetrate the food. Osmotic drying operates as a mass transfer mechanism. It is noteworthy that the sensory characteristics of fresh and sliced fruits, including color, texture, aroma, and flavor, are enhanced through this process, all while preserving their structural integrity. This enhancement contributes to the overall nutritional quality by increasing the bioactive content and enhancing both color and texture (Özkan-Karabacak et al., 2022). The process of osmotic dehydration (OD), involving the infusion of fruits with solutes, has gained considerable popularity as a method for enhancing fruits with health-promoting substances (Macedo et al., 2021).

The OD or impregnation method offers advantages such as low energy demand, serving as a partial moisture removal technique. This, in turn, reduces the subsequent drying time required for the product to achieve shelf stability. This combined successive drying process is notably efficient, facilitating the production of a stable end product in a relatively short time. (Saleena et al., 2021; Özkan-Karabacak et al., 2022).

The OD has the potential to greatly improve the freshness and sustainability of fresh fruit. Furthermore, osmo-impregnation holds significant industrial potential for developing fruit and vegetable products enriched with bioactive ingredients.

2 Methodology

A comprehensive literature search was undertaken, employing the bibliographic review methodology as described by Jaramillo-Zárate & Londoño-Giraldo (2023). Focusing on the most recent five years (2018-2023), this investigation encompassed a thorough exploration of scholarly works within ScienceDirect, PubMed, and Google Scholar databases, targeting pertinent literature concerning the subject of interest. Furthermore, articles published from 2012 to 2017 were incorporated into the review to ensure the inclusion of relevant studies pertaining to the processes of OD of food and the osmo-impregnation of fruits and vegetables. This extended timeframe was considered necessary to include any potentially relevant articles that might not have been included by the specified temporal scope. The primary keywords employed in the search queries included “osmotic drying,” in conjunction with the Boolean operator “AND” for a particular emphasis on impregnation and the fortification of nutrients. These nutrients encompassed categories such as “vitamins,” “minerals,” “phenolic contents,” “prebiotics,” and “probiotics,” among others. Additionally, search terms encompassed “osmo-combined drying techniques” in conjunction with the Boolean operator “OR,” with respect to alternative methodologies like “vacuum,” “ultrasound,” and “pulse electric field,” among others. The specification of the search queries further encompassed terms such as “osmotic dehydration,” “fortification or impregnation,” or the specific bioactive compounds of interest. This approach was structured to target the research area's nuances, focusing on specific compounds like “vitamin C,” “vitamin B,” “calcium,” “dietary fibers,” and “beneficial microorganisms,” among others. Therefore, some of the search terms used were:

- “food fortification” AND “osmotic dehydration”;
- “osmo-dehydrated fruit,” AND (“recent trends,” OR “alternative sweetener”);
- “osmo-dehydrated vegetables,” AND (“recent trends,” OR “alternative sweetener”);
- “osmotic dehydration,” AND “impregnation,” AND “bioactive components”;
- “osmotic dehydration” AND (“nutrient” OR “disease prevention”) AND “vegetables”;
- “osmotic dehydration” AND “nutrient” AND (“fruit” OR “vegetables”).

Upon data retrieval from the database, the acquired information underwent correlation analysis using VOSviewer (Java version 1.8.0_261). This analytical process involved the use of keywords derived from a comprehensive review of studies associated with the practices of OD and impregnation. The Boolean connector “AND” was employed to ascertain the conjunction of these two processes. Furthermore, to encompass the diversity of terminology used in the literature, the Boolean connector “OR” was applied to capture an array of bioactive components and advanced osmo-combine techniques. The outcomes of this analysis were subsequently ranked based on term co-occurrence, with particular emphasis on the statistical relationships between terms. The program's suggested link strength, while available, was not considered in the ranking process, thereby emphasizing the intrinsic associations between the identified terms.

The findings are focused on a selection of current articles on the topic of interest, although, as can be seen below, due to the limited research development on food fortification by OD, there will be more publications with dates earlier than the time range used.

3 Fortification potential of osmotic dehydration for fruits and vegetables

In fact, OD is regarded as a practical method for incorporating functional ingredients, primarily due to its ability to have minimal negative effects on the food matrix. However, the extent of these effects depends on the specific drying technique and osmotic agent used in the process (Macedo et al., 2022). This process results in a slight reduction in water activity. When combined with other mild practices, refrigerated storage, or a subsequent application of combined drying, it enhances the microbiological stability of the product and effectively retains the key attributes of fresh fruit (Stavropoulou et al., 2022). OD emerges as a significant approach for introducing beneficial microorganisms, minerals, vitamins, phytochemicals, and other valuable constituents into the food matrix (Escobedo-Avellaneda et al., 2018).

3.1 Mineral and vitamin fortification via osmotic dehydration

The consumption of fortified foods containing essential minerals can enhance health maintenance and contribute to disease prevention. Fruits and vegetables, naturally deficient in minerals like calcium (Ca) and zinc (Zn), can undergo various techniques to increase their concentration (Bellary & Rastogi, 2016). As one of the most vital minerals, calcium plays a critical role in the development, maintenance, and reproduction of the human body. Unfortunately, there is a scarcity of high-quality dietary sources of calcium, particularly in cases where milk and dairy products are not regularly consumed. To address the inconsistency between calcium intake and recommended levels, manufacturers are progressively introducing a variety of calcium-fortified products into the market (Singh et al., 2007).

The addition of calcium salt into osmotic solutions worked as an effective approach for improving structural damage induced by cell walls throughout the dehydration process. This approach reduced the adverse effects of dehydration and sustained the structural integrity of cell walls (Ferrari et al., 2010). On the other hand, the incorporation of calcium salt into osmotic solutions yielded positive outcomes, including the acceleration of water loss, a reduction in water activity, and an elevation in the calcium content of fruits and vegetables, consequently resulting in fortified end-products (Silva et al., 2014b). OD with the inclusion of calcium salt increases nutrient fortification in fruits and vegetables, thereby enhancing their mineral content, with potential effects for improved health maintenance and disease prevention.

Pear slices were subjected to OD/impregnation in an aqueous solution containing 5% of lactate calcium and 1% of zinc for a duration of one hour. Subsequently, a combined drying process was implemented, involving simultaneous microwave and hot air convection, over a brief period of 10-12 minutes. This process yielded a stable product with a 20% of moisture content and increased the concentration of original potassium in pears, resulting in a final product with 193 mg of potassium per 100 grams. As a result of the finished product meeting 20 to 50% of the daily dietary requirements for calcium and zinc per serving, therefore, it is characterized as an enriched food product (Della Rocca, 2021).

OD was investigated as a method to fortify calcium in pumpkin flesh. The results indicated that, by carefully selecting process parameters, it is feasible to significantly enhance the calcium content within the plant matrix, providing notable benefits for individuals at risk of osteoporosis. Specifically, pumpkin pulp dehydrated in solutions with 50% of xylitol and inulin, along with 5% of calcium carbonate, exhibited the highest calcium content, measuring 1,380.4 and 1,328.4 mg Ca per 100 grams, respectively (Kulczyński et al., 2021). The addition of sugar beet molasses to osmotic solutions was observed to significantly increase the mineral content, including calcium, potassium, magnesium, and iron, in fruits and vegetables, thereby enhancing their nutritional composition. This effect was especially prominent in apples and carrots, where a notable increase in mineral concentration, specifically potassium, magnesium, and calcium, was observed following treatment with sugar beet molasses (Koprivica, 2013). Rodríguez-Ramírez et al. (2023) conducted a study on chilacayote tissue samples, subjecting them to immersion in $Ca(OH)_2$ solutions for varying durations (1.5, 3.0, and 4.5 hours) at concentrations of 0.5, 1, and 1.5 g/100 mL of water, and at solution temperatures of 20, 35, and 50 °C. Following this calcium pretreatment, the materials underwent OD for two hours, using sucrose solutions at different concentrations (30, 45, and 60 °Brix) and temperatures (30, 50, and 70 °C). The interaction of Ca^{2+} ions with chilacayote tissue resulted in a significant increase in calcium content. The most effective treatment, combining osmosis (45 °Brix, 50 °C, and 2 hours) with calcium pretreatment (1 g/100 mL water, 35 °C, and 3 hours), produced a minimally treated product with intermediate moisture, achieving a remarkable 100% gain in calcium content. The above-mentioned studies collectively demonstrate that OD serves as an effective method to enhance nutrient fortification in a variety of fruits and vegetables, resulting in enriched foods with elevated mineral content and thus contributing to improved nutritional value.

Nevertheless, it is worth noting that OD of fruits and vegetables using sugar beet molasses has been linked to the darkening of the treated samples. The degree of darkening was observed to depend on the duration of immersion and the concentration of the molasses solution. A notable application of osmotically dehydrated fruits and vegetables treated with sugar beet molasses is their successful incorporation into wheat bread formulations. Reports indicate that both wet and powdered osmotically dehydrated fruits, such as apples, plums, carrots, and red cabbage, can be successfully incorporated into bread recipes (Filipčev et al., 2010; Šarić et al., 2016). While sugar beet molasses may induce darkening, impacting the color quality of the treated samples, it simultaneously aids in the preservation of fruits and vegetables during the OD process.

An investigation was conducted to explore the feasibility of fortifying goods with added calcium using minimally processed apples. For this study, a solution containing apple samples was supplemented with citric acid, 1500 ppm potassium sorbate, 10.9% of glucose, and 5266 ppm calcium salt, which was a blend of calcium lactate and calcium gluconate. The experiment contained two conditions: one conducted with vacuum application and the other without vacuum. The results of this investigation revealed that the process conducted without the use of vacuum proved to be more effective in terms of tissue impregnation capacity. Specifically, the amount of calcium integrated into the apple samples reached 1300 ppm after 6 hours of processing without vacuum, and this content increased to 3100 ppm after 22 hours. In contrast, impregnation achieved through the vacuum method ranged between 1150 and 2050 ppm, demonstrating a lower efficacy in Ca incorporation. This study revealed that OD, when performed without vacuum application, is more effective for impregnating apples with calcium, resulting in a higher calcium content in the final product (Anino et al., 2006).

Through the utilization of calcium-enriched sucrose solutions, a research investigation was conducted to assess the impact of OD on the calcium content of pineapple. The outcomes revealed that OD of pineapple in calcium-enriched sucrose solutions led to a notably increased calcium content and a decreased sugar content in the fruit. Specifically, the samples with the highest calcium content were able to provide 10% of the daily calcium requirement from 100 g of the product following OD for 6 hours in a solution containing 4% of calcium lactate. Furthermore, the fruit exhibited an elevated calcium content even after just two hours of OD, in addition to having a lower sucrose content compared to samples treated with a calcium-free solution (Silva et al., 2014a). The OD using calcium-enriched solutions serves to enhance the calcium content of pineapple while alongside reducing the sugar content, thereby elevating its overall nutritional value.

The effectiveness of OD in preserving and enhancing the nutritional content of mangoes and fresh-cut apples was investigated. Enrichment with ascorbic acid during mango OD was found to positively influence total phenolic contents (TPC), with no discernible losses once interferences were accounted for. In fresh-cut apples, vacuum impregnation (VI) with vitamin E, high fructose corn syrup, calcium caseinate, and hydroxypropyl methyl cellulose (HPMC) resulted in elevated levels of α-tocopherol acetate, calcium, and zinc, thus demonstrating the potential of these methods for nutritional enhancement in food processing (Zhao et al., 2005).

Jahan et al. (2019) conducted a study that revealed promising potential for the processing of pineapple as a value-added product through the application of OD and/or air drying techniques. In pineapple processing, OD proved beneficial in preserving vitamin C content by reducing its degradation rate during subsequent air drying, thereby enhancing the overall quality of the product.

Fruit juice concentrates provide a practical alternative osmotic agent for increasing the nutritional value of dehydrated fruits by increasing their natural sugar content and elevating their composition with bioactive compounds. This offers a beneficial alternative to using sucrose solutions in the OD process. Specifically, the use of chokeberry, strawberry, and cherry juice concentrates has shown promising benefits in this context. To explore the dehydration process, strawberries were subjected to OD employing fruit juice concentrates (chokeberry, strawberry, or cherry), with a sucrose solution employed as a control. The process was conducted at a temperature of 30 °C for 3 hours. The application of OD with fruit juice concentrates showed to enhance the incorporation of vitamin C and anthocyanin, thus elevating the nutritional profile of dehydrated fruits (Kowalska et al., 2023).

3.2 Polyphenolic content fortification via osmotic dehydration

The addition of chokeberry juice concentrate to the osmotic solution significantly contributed to a substantial increase in the fruit's polyphenol content. These findings suggest that both inulin and concentrated chokeberry juice can be effectively employed as beneficial osmotic agents. Strawberries subjected to osmotic pretreatment, followed by freeze-drying and a microwave convective drying process, can be enjoyed as a delicious snack or added as a desirable component to various products (Kowalska et al., 2019). Jiménez-Hernández et al. (2017) investigated the OD of mango slices utilizing an emulsion containing inulin and piquin-pepper oleoresin. After a 120-minute treatment, the mango slices were evaluated for their impact on water loss, solids gain, oil gain, color alteration, β-carotene, ascorbic acid, and TPC. Furthermore, their capacity to neutralize free radicals and inhibit the growth of cancerous breast tissue (MDA-MB-231) was investigated. The highest oil gain and retention of bioactive components were noted in samples treated with the emulsion at a temperature of 40 °C. At 40 °C, OD employing an emulsion of inulin and piquin-pepper oleoresin effectively enhances mango slices with bioactive constituents, potentially positioning them as a functional and anticancer food source notably rich in phenolic compound.

The optimal conditions for osmotic drying to infuse slices of yam bean tuber with anthocyanin were investigated. Following 6 hours of osmotic drying, the impact of temperature (40, 50, and 60 °C), sucrose content (40, 50, and 60 °Brix), and vacuum pulse (0, 300, and 600 mbar) on water loss, solid gain, color changes, and anthocyanin concentration was examined. The findings suggest that the most significant anthocyanin impregnation took place at an osmotic solution temperature of 60 °C, a sucrose concentration of 40 °Brix, and a vacuum pulse of 12 mbar. Under these conditions, 6.67 mg of anthocyanin per gram of original dry matter was achieved. OD emerges as an effective method for augmenting anthocyanin impregnation in yam bean tuber slices, leading to an increased concentration of this beneficial compound and enhanced nutritional value (Grajales-Lagunes et al., 2019).

3.3 Probiotics and prebiotic fortification via osmotic dehydration

Probiotics are considered a cost-effective and safe alternative for managing various chronic illnesses and promoting human health. These microorganisms have shown the ability to regulate the host's immune response and provide protection against a range of infectious and non-infectious disorders. Various attributes of probiotics influence their interactions with the host, including their capacity to colonize, eliminate pathogens, and stimulate host cells. Moreover, prebiotics and non-digestible food components play a beneficial role in fostering the growth of probiotics, thereby promoting human health through the regulation of the immune system, improved nutrient absorption, and the modification of gut microbiota (Yadav et al., 2022).

The consumption of functional foods containing probiotics has experienced a surge in popularity in recent years, especially within the non-dairy market. This trend is driven by increased consumer awareness of the relationship between diet and health, along with a shift in consumer preferences toward healthier dietary choices. As a result, there is a substantial demand for the development of fruits and vegetables enriched with probiotics to satisfy the needs of consumers seeking these health-promoting foods. While the development of probiotic-rich foods has traditionally focused on dairy products, the increasing trend towards non-dairy alternatives offers a promising opportunity for growth in this field (Puente et al., 2009; Vijay et al., 2021).

Probiotic bacteria were introduced into dehydrated pineapple slices through osmotic infusion in a sucrose-based solution. The study demonstrated significant uptake of *Lactobacillus plantarum* and *L. casei*, successful infusion at both surface and sub-surface levels, and remarkable viability under simulated gastrointestinal stresses. After 10 days of storage at minus 20 °C, the infused probiotics maintained a vitality of over 6 log CFU/g, suggesting that osmotically dehydrated sliced pineapple infused with probiotics is a potent non-dairy probiotic food with a satisfactory shelf life (Vijay et al., 2021).

Lactobacillus plantarum was effectively incorporated into apple cubes through OD at 37 °C, under pressure conditions of 10^{13} or 150 mbar, and using osmotic solutions with sucrose or sorbitol at concentrations of 40 °Brix or 60 °Brix. The study revealed successful incorporation at concentrations ranging from 10^7 to 10^8 cfu/g, with a preference for 40 °Brix solutions. The sustainability of *L. plantarum* remained at 10^7 cfu/g during six days of storage at 4 °C, and the probiotic displayed substantial survival throughout a 2-hour simulated digestion replicating digestive tract conditions (Emser et al., 2017). These studies collectively highlight that OD effectively enhances the incorporation and survival of probiotic bacteria in fruits such as pineapple and apple, resulting in effective non-dairy probiotic foods with extended shelf life and resilience to gastrointestinal conditions.

Prebiotics enhance the immune system and support probiotic growth in the gut. Consuming fermented foods, a natural habitat for probiotics, plays a crucial role in managing health conditions, promoting overall well-being by improving gut health through the positive effects of prebiotics (Ahlawat et al., 2021). Inulin is a type of prebiotic dietary fiber that offers numerous potential health benefits. It is known to reduce caloric intake and help lower blood glucose and plasma lipid/cholesterol levels when used as a substitute for sugar and fat. In addition, its diverse nutritional and functional properties make it a highly valued ingredient in the food industry (Abed et al., 2016; Teferra, 2021).

OD of plums in a solution comprising water, glycerol, and inulin was employed to assess water loss, weight reduction, inulin gain, and glycerol gain. The results indicated that, under optimal conditions, the achieved values were 30% for water loss, 29% for weight reduction, 119 mg/g for inulin gain, and 373 mg/g for glycerol gain. This suggests that OD of plums, when used as a pre-treatment before conventional drying, proves to be a valuable approach for reducing water content while simultaneously enhancing the inulin content of the final products (Palacios Romero et al., 2022).

Fructooligosaccharides (FOS) represent a class of non-digestible oligosaccharides that have gained considerable attention in recent research focusing on the OD of fruits and vegetables. FOS possess attributes of dietary fiber and prebiotics, indicating their potential to enhance the proliferation of beneficial gut microorganisms and facilitate calcium absorption. Their distinctive properties make them a promising choice as an osmotic agent in various applications (Rubio-Arraez et al., 2015).

OD utilizing complex solutions, including non-digestible oligosaccharides and sucrose, was explored on tomatoes. Various solutions, including oligofructose, a sucrose-oligofructose mixture, an isomaltulose-oligofructose blend, and a polydextrose-oligofructose blend, were investigated. The study aimed to optimize the OD treatment based on color, firmness, and mass exchange indices. Oligofructose, especially in combination with short treatment times, yielded the highest desirability, resulting in substantial solid gain (associated with oligofructose incorporation) while preserving quality attributes like color, texture, and sensory characteristics (Giannakourou et al., 2020).

In another study, prebiotics (such as inulin, FOS, and sucrose solutions) were explored for use in the OD of Andean blackberries. Results revealed that osmotic solution concentration and prebiotic molecular size significantly affected weight reduction and water loss. Inulin and FOS showed less solute diffusion into blackberries than sucrose, indicating potential for creating stable, functional products enriched with prebiotic substances in the food industry (Rodriguez-Barona et al., 2014).

The selection of osmotic solutions and treatment durations can be intricate, often requiring optimization to achieve the desired results, which adds complexity to the process. However, the use of non-digestible oligosaccharides such as inulin and FOS in OD enriches fruits and vegetables with prebiotic compounds, thereby enhancing their nutritional value and offering potential health benefits. Table 1 presents a compilation of the key findings related to this subject matter.

Table 1. Bioactive components fortification by osmotic dehydration (OD) process.

Commodities	Bioactive component	Health benefits	References
Mango	Inulin	Prebiotic	Jiménez-Hernández et al. (2017)
Gooseberry	Fructooligosaccharide (FOS)	Prebiotic	Nambiar et al. (2016)
Apple	Green tea extracts (GTE)	Flavonoids	Tappi et al. (2017)
Banana	Curcuminoid	Anti-inflammatory, antimicrobial, antioxidant	Bellary & Rastogi (2014)
Coconut	Curcuminoid		Bellary et al. (2011)
Banana	Lactobacillus	Probiotic	Rascón et al. (2018)
Strawberry	Inulin	Probiotic	Kowalska et al. (2017)
Apple	Lactobacillus	Probiotic	Flores-Andrade et al. (2017)
Apple	*Lactobacillus plantarum*	Probiotic	Emser et al. (2017)
Apple	*Lactobacillus casei*	Probiotic	Betoret et al. (2003)
Apple	Calcium	Mineral	Barrera et al. (2004)
Grapefruit	Calcium	Mineral	Moraga et al. (2009)
Apple and banana	Phenolic content	Antioxidant	Rózek et al. (2010)

4 Osmo-combined techniques for fortification in fruits and vegetables

The OD is known for its relatively slow process. However, various osmo-combined procedures, including VI, pressure vacuum OD, sonication, microwave, and others, have demonstrated that treatments capable of significantly damaging or disrupting cellular structures can accelerate mass exchange kinetics. These treatments influence the cell wall to enhance water transport through the cell membrane, consequently increasing the diffusion rate throughout the drying processes (Veloso et al., 2021). The incorporation of bioactive compounds into solid foods has been the focus of extensive research, leading to the development of various techniques (Figure 1). In the field of osmo-combination, common methods include vacuum-assisted osmotic fortification, ultrasound-assisted osmotic (UAO) fortification, and pulse electric field-assisted (PEF-assisted) osmotic fortification. These approaches have been well-documented in the pertinent literature and have demonstrated their effectiveness in increasing the bioavailability and functional characteristics of food products.

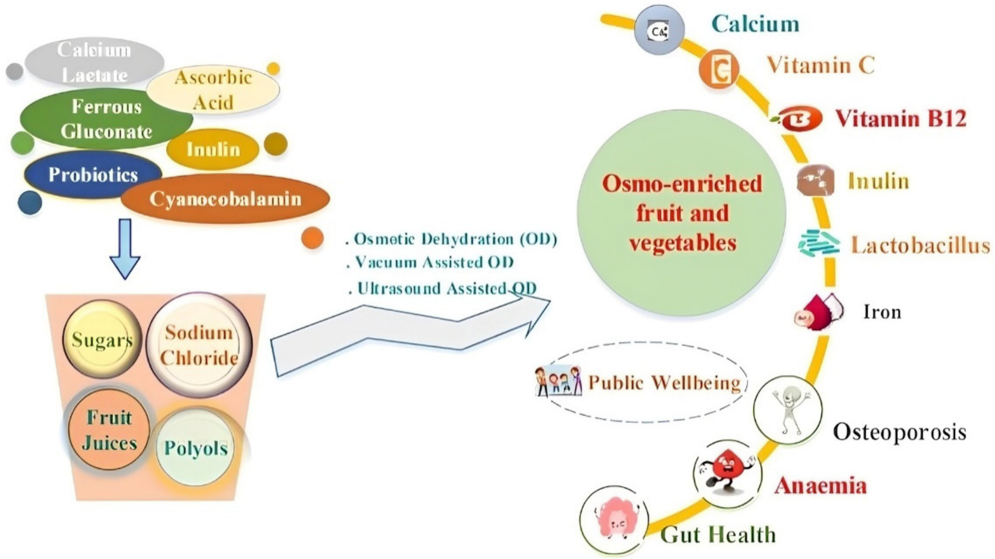

Figure 1. Process diagram of impregnation by osmotic dehydration.

4.1 Vacuum assisted osmotic fortification

In fact, VI is an innovative technique used in the field of OD for porous food products, resulting in substantial alterations to food composition. VI effectively promotes the transfer of internally trapped gases or liquids from open pores into an external liquid phase by utilizing hydrodynamic mechanisms in conjunction with controlled pressure fluctuations. This process significantly enhances food quality by modifying its composition. Particularly, VI offers a distinct advantage by impeccably incorporating both osmosis and diffusion as integral components of its operational process (Sasireka & Ganapathy, 2016).

Le & Konsue (2021) explored the impact of increased vacuum pressure and the addition of calcium lactate (Ca-L) during OD of "Phulae" pineapple. Higher vacuum pressure enhances solute uptake and water loss, while Ca-L decreases yellow hue, color acceptability, and TPC. However, a 2% of Ca-L concentration significantly raises calcium content, fulfilling 31.25% of daily needs and ensuring high acceptability and sensory scores. This approach demonstrates a practical means to enhance the nutritional value of pineapple products through OD.

The use of fruit juice concentrates as an osmotic agent, coupled with subsequent drying, is gaining popularity and contributing to the attractiveness of the final product (Samborska et al., 2019; Kowalska et al., 2020a). Pasławska et al. (2019) employed infiltration solutions consisting of apple-pear juice, a 3% of citric acid solution, and distilled water, followed by hot air finishing drying. The study investigated various process parameters in the VI of apple tissue, including vacuum levels (4, 6, or 8 kPa) and durations (10-80 seconds), with an atmospheric stage (4 minutes). Higher vacuum levels resulted in increased mass transfer strength, which is advantageous for including bioactive components. Optimal results were achieved with a 4 kPa vacuum for 40 seconds, enhancing mass transfer and retaining native bioactive components in infused apple cubes. This approach presents a favorable method for incorporating bioactive compounds into apple tissue.

In another study, Caballero et al. (2021) employed an isotonic sucrose solution (14 °Brix) containing 10^{10} cfu/g of *Bacillus coagulans* to impregnate apple slices. Vacuum pressures (22, 29, 36, and 43 cm Hg) were applied for 5 minutes, with relaxation times ranging from 35 to 204 minutes. The maximum vacuum pressure (43 cm Hg) consistently yielded a high concentration of *B. coagulans* cells (4×10^7 cfu/g) in apple slices, comparable to commercial probiotic products. Utilizing a 43 cm Hg vacuum for 5 minutes, along with varied relaxation times, proves to be an effective method for achieving high *B. coagulans* concentrations in apple slices, making them a suitable matrix for probiotic incorporation.

The combined impact of OD and vacuum impregnation (OD-VI) at standard atmospheric pressure on mango cubes was studied. The OD solution consisted of 60 °Brix sucrose, 2% of calcium lactate, and varying concentrations of pectin methylesterase (PME). Results demonstrated that OD with PME was highly effective, yielding osmotically dried mangoes with minimal sugar uptake and optimal preservation of vitamin C (20.3 mg per 100 g). The synergy of OD and VI not only enhances vitamin C content but also reduces sugar gain, providing a significant improvement in health benefits and nutritional value for dried mangoes (Sulistyawati et al., 2020). The combined effects of VI and high-pressure pretreatment, along with the incorporation of PME into the osmotic solution, were investigated for their impact on the quality of osmotically dehydrated mangoes at various ripeness stages. The amalgamation of VI with high-pressure pretreatment, along with PME inclusion, demonstrated a significant improvement in firmness and the preservation of color parameters in osmotically dehydrated mangoes, irrespective of their ripeness stages (Sulistyawati et al., 2018).

After undergoing various pre-drying methods, including air-drying, microwave-drying, and freeze-drying, strawberries, carrots, corn, and blueberries were subjected to a VI process using a nanosized calcium carbonate solution. The preparation involved a solution with lecithin, milk powder, nano-calcium carbonate, and sugar, blended with cocoa butter under controlled conditions. The impregnation solution, with 45% of sugar, 3% of nano-calcium carbonate, and 0.3% of lecithin, was applied using the ZJ-300 impregnation apparatus. This process exhibited a synergistic effect, leading to significant impregnation of functional compounds and an overall enhancement in the quality of the final products for all fruits (Gong et al., 2009).

A combined method of VI and OD, using a 55 °Brix sucrose solution, was employed to produce calcium-fortified apple slices. The study revealed that introducing calcium into the apple slices during manufacturing increased yield, particularly at lower temperatures (30 °C to 40 °C) and with the addition of 1% calcium lactate. Maintaining fortification levels during VI was achievable by incorporating a specific concentration of calcium salt into the osmotic solution. Despite some calcium loss during VI, OD effectively enhanced shelf life without significant nutritional content reduction. Reduction in water content decreased as calcium content increased, ranging from 0% to 40% of recommended daily allowances in a 200 g sample. Although there is some calcium loss during VI, the combined OD and VI technique enhances both yield and shelf life of calcium-fortified apple slices (Barrera et al., 2009).

González-Pérez et al. (2023) aimed to maximize beta-carotene content in 1 mm diameter, 2 mm length jicama cylinders through osmotic impregnation using carrot juice. Key factors considered were osmotic agent concentration (20, 35, and 50 °Brix) and immersion time (20, 30, and 40 minutes). Optimal parameters were determined as 31 minutes immersion time and 50 °Brix concentration, resulting in jicama cylinders with 269 mg beta-carotene per 100 g. The synergistic effect of osmotic impregnation with carrot juice at 51 mm Hg pressure infused a high beta-carotene concentration, potentially offering health benefits in preventing specific diseases.

Another study compared the enrichment of beta-carotene in apple slices through pulsed-vacuum OD and conventional OD using sucrose solutions ranging from 30 to 50 °Brix. Results indicated an increase in beta-carotene content from 1.5 to 4.1 mg/g during OD and from 4.7 to 6.0 mg/g during pulsed-vacuum OD as the concentration of the osmotic solution increased. Higher sucrose concentrations enhanced impregnation, leading to greater beta-carotene enrichment. The study concludes that higher sugar concentrations create a stronger osmotic pressure gradient, resulting in increased mass exchange during osmotic processes. Additionally, the use of pulsed-vacuum OD techniques shows promise in enhancing bioactive compound impregnation, offering potential optimization for increased fortification in apple slices (Santacruz-Vazquez et al., 2008).

Osmotic processes were evaluated under varying atmospheric and reduced pressures. The primary objective was to synthesize osmo-dehydrated eggplant slices with reduced sodium content by substituting potassium chloride and calcium chloride. The application of vacuum notably improved the retention of ascorbic acid (29.33% increase) and calcium (85.06% increase). However, the use of vacuum also led to increased water loss (up to 53%), attributed to heightened incorporation of ions, particularly potassium ions. The combined approach of reduced pressure and sodium replacement presents innovative prospects for creating healthier food products. The synergy demonstrated improved retention of both ascorbic acid and calcium in osmo-dehydrated eggplant slices, offering promising potential for the development of more nutritious food alternatives (Jesus Junqueira et al., 2017).

The utilization of high pressure has been shown to enhance sucrose diffusion in potato cylinders (Sopanangkul et al., 2002). A comprehensive study was conducted to explore the impact of OD and high hydrostatic pressure on the preservation of strawberry antioxidant capacity, phenolic compounds, color, and vitamin C during refrigeration. The objective was to gain insights into the effectiveness of this combined preservation method. In this study, commercial sugar was used to create an osmotic solution, and samples were subjected to pressures ranging from 100 to 500 MPa for 10 minutes. Particularly, at 400 MPa, samples showed significant vitamin C content, increased antioxidant activity, and an overall increase in phenolic content. Combining OD and high hydrostatic pressure at 400 MPa for 10 minutes resulted in enhanced antioxidant activity and increased phenolic content in strawberries, indicating a synergistic preservation effect on nutritional parameters (Nuñez-Mancilla et al., 2013).

Indeed, VI was highlighted as a technique with potential for integrating bioactive compounds, such as carotenoids, ascorbic acid, and calcium lactate. The increase of osmotic agent concentration positively influenced mass transfer parameters, leading to increased water loss, weight reduction, reduced water activity, and enhanced impregnation of total soluble compounds. Consequently, VI emerges as a straightforward and efficient technique for incorporating physiologically active substances into the porous structure of fruits and vegetables. In conclusion, pulse vacuum osmotic dehydration (PVOD) resulted in a significant impregnation of functional compounds within the final product (González-Pérez et al., 2023; Wagh et al., 2023).

The application of PVOD for the enrichment of antioxidant compounds and essential nutrients is a subject of ongoing investigation. The process is characterized by a relatively low removal of water from the food due to its water-absorption properties, coupled with a substantial increase in solid content. This property is particularly advantageous for effectively enriching the sample with bioactive compounds (Sittisuanjik et al., 2021).

4.2 Ultrasound (sonication) assisted osmotic fortification

The dehydration of fruit or vegetable particles can be achieved through two approaches: direct dehydration using ultrasound (sonication) treatment or an indirect method involving pre-treatment before OD. The combination of sonication with the OD process has the potential to further enhance dehydration efficiency by enhancing mass transfer rates and elevating the quality of the final product (Salehi et al., 2022). An investigation explored the impregnation of apple cubes with vitamin B12 (cyanocobalamin) using ultrasound. The application of ultrasound was found to enhance the impregnation process, resulting in apple cubes with increased cyanocobalamin content ranging from 0.12 to 0.19 mg vitamin/g dry basis. The results suggest that ultrasound-assisted impregnation is a promising method for producing apple cubes enriched with vitamin B12 (Vasile et al., 2022). The study developed a probiotic snack using apples and *L. rhamnosus GG*. Ultrasound-assisted OD followed by conventional drying preserved sufficient live probiotic cells (10^6 to 10^7 cfu g^{-1}). The resulting dried apple snack qualifies as a probiotic product, showcasing enhanced microbial survival (Saydam et al., 2019).

Ultrasound-assisted osmotic dehydration (UAOD) effectively increased ascorbic acid content in plantain slices at 60 °C with 60% of sucrose. Treatment with 45% of sucrose at 40 °C resulted in a notable rise from 18% to 42%. The approach enhances ascorbic acid impregnation while preserving slice quality, promising for elevating the nutritional profile of plantain snacks (Martínez-Sánchez et al., 2022).

Alizehi et al. (2020) explored the impact of various treatments on osmo-dehydration and spouted bed drying (SBD) of carrot cubes, including vacuum treatments, ultrasound power levels, air-drying temperatures, infrared power, and the introduction of teflon beads (inert carrier particles with the potential to accelerate drying). Compared to OD alone, the use of UVOD (osmo-dehydration with ultrasound and vacuum) significantly reduced drying time. UVOD-treated samples showed the least total color difference and the highest total carotenoid concentration.

The combination of vacuum and ultrasound treatments with OD synergistically improves moisture removal, solid gain, and fortification processes. Simultaneously, the inclusion of high molecular weight carbohydrates and water-soluble proteins reduces sugar uptake. This integrated approach offers an effective method for enriching food materials with health-promoting substances (Wang, 2022).

4.3 Pulse electric field assisted osmotic fortification

In pulse electric field (PEF) technology, biological materials are positioned between two electrodes and exposed to short-duration, high-voltage pulses. The external electric field leads to electroporation of the tissue, which can occur in two forms: transient or irreversible. When the intensity of the electric field exceeds a specific threshold, it results in a temporary permeabilization of the cell membrane. However, if the electric field strength remains below the irreversible electroporation threshold, the cells have the capacity to recover their membrane integrity and maintain their normal functionality after exposure to the electric field. The use of reversible electroporation is a feasible approach for delivering a wide range of functional substances into plant tissues while preserving the viability of the electrically stimulated cells. This is possible because the pores formed in the cell membranes due to the electric field promptly reseal upon the removal of the electrical field (Tylewicz, 2020). The study investigated the impact of PEF pre-treatment on OD, revealing that PEF enhanced the movement of water and solutes by accelerating effective diffusion coefficients. This highlights a significant improvement in the efficiency of the OD process (Paraskevopoulou et al., 2022). The impact of PEF and OD pre-treatments on goji berry drying was investigated. PEF induced tissue permeabilization, facilitating mass transfer during OD and subsequent air drying. The combined PEF and OD pre-treatments with air drying reduced processing time by 33%, improved color retention, increased antioxidant capacity, and enhanced TPC in goji berries. This approach shows potential for enhancing final product quality compared to conventional air drying methods (Dermesonlouoglou et al., 2018).

A yellow kiwifruit dried snack with exceptional nutritional properties was developed by combining air drying, OD, and PEF techniques. Various pretreatments, including PEF and/or OD, were assessed for their impact on color, bioactive compound concentration, and antioxidant activity. Optimal color preservation was achieved at a drying temperature of 60 °C, with kiwifruit snacks subjected to OD and PEF pre-treatment showing substantial retention of total polyphenols, vitamin C content, and antioxidant activity. The synergistic effect of OD and PEF in kiwifruit drying not only improved nutritional properties but also potentially enhanced sustainability by reducing drying time and energy consumption (Mannozzi et al., 2020). The OD in apples was optimized through PEF treatment, resulting in maximum mass reduction. The number of pulses significantly influenced water loss and solid gain, providing valuable insights for process enhancement (Nazari et al., 2019).

5 Advantages and disadvantages

Osmo-fortification and osmo-combined techniques offer diverse advantages in enhancing nutritional profiles; however, careful management of processes is crucial to alleviate potential drawbacks and ensure consumer satisfaction and adherence to nutritional guidelines. The advantages and drawbacks are outlined in Table 2.

Table 2. Advantages and disadvantages of osmo-fortification and osmo-combined techniques.

Advantages	Disadvantages	References
Osmotic dehydration (OD) enriches fruits and vegetables with essential minerals, vitamins, polyphenols, probiotics, and prebiotics, enhancing their overall nutritional value.	Osmotic dehydration (OD) may induce changes in texture, flavor, and color, impacting consumer preferences and the overall quality of fortified products.	Escobedo-Avellaneda et al. (2018); Macedo et al. (2022)
Osmo-fortification helps retain bioactive components such as polyphenols, anthocyanins, and antioxidants, contributing to improved health benefits and antioxidant properties.	Selecting osmotic solutions and treatment durations for prebiotic fortification can be intricate, requiring optimization and adding complexity to the process.	Kowalska et al. (2019); Saric et al. (2016)
Probiotic-infused fruits maintain viability over time, offering non-dairy probiotic foods with an extended shelf life and resilience to digestive conditions.	The addition of certain agents may lead to darkening of treated samples, affecting color quality, though this may aid in product preservation.	Vijay et al. (2021); Emser et al. (2017)
The use of various prebiotics in OD provides flexibility, enriching fruits with different prebiotic compounds that contribute to improved gut health.	Success in osmo-fortification relies heavily on controlling parameters like temperature and duration, demanding precision in execution.	Palacios Romero et al. (2022)
Osmo-fortification allows for tailored nutrient profiles, meeting specific dietary requirements and preferences through precise control of process parameters.	Without careful control, there is a risk of over-fortification, leading to undesirable levels of certain compounds and potential health implications.	Della Rocca (2021)
Osmo-combine techniques in fruit and vegetable processing enhance dehydration efficiency, accelerating the osmotic process and reducing drying time compared to OD alone.	Specific conditions, osmotic concentrations, and equipment required for optimal outcomes.	Veloso et al. (2021)
The osmo-combine techniques increase impregnation, allowing for a more uniform distribution of beneficial bioactive components within the fruit.	Potential challenges in scaling up for large-scale production.	Martínez-Sánchez et al. (2022)

6 Utilizing non-traditional osmotic solutes for enhanced nutritional profiles

In the field of OD, there is a growing trend towards utilizing non-traditional osmotic solutes, particularly functional compounds and components characterized by high nutritional value and a low glycemic index. Research has shown that the complete or partial replacement of conventional sugars like sucrose and fructose with sugar alcohols such as glycerol, as well as the incorporation of sorbitol, can significantly improve mass transfer rates and enhance the overall quality of osmo-dehydrated fruits and vegetables. This, in turn, leads to better preservation of texture, moisture, and color (Dermesonlouoglou et al., 2019). During OD, oligofructose, a type of FOS, was used as the osmotic solute. Oligofructose is renowned for its outstanding qualities as a dietary fiber, rendering it a fitting choice for application as an osmotic solute (Rubio-Arraez et al., 2015). In addition to traditional sweeteners, alternative options such as maltodextrins, fruit juices (carbohydrate-based sweeteners), and stevia (a non-carbohydrate sweetener) are commonly utilized as osmotic agents in the OD process. These alternatives are often preferred by individuals with specific health concerns, including diabetes, obesity, or dental caries (Kumari et al., 2020).

Erythritol and xylitol, along with sucrose, were utilized in the OD of apple slices for a duration of two hours. Subsequently, various drying techniques were employed, including convective drying (CD), microwave-vacuum drying (VM), and a combined approach CD/VM. The study revealed that the concentration of polyols in the final product is well within safe limits and does not lead to gastrointestinal issues. This highlights the potential advantages of utilizing sugar alcohols in OD to produce dried snacks that are not only healthier but also safer for consumption (Cichowska-Bogusz et al., 2020). Trehalose has gained increasing attention as an osmotic solute in OD due to its capacity to protect proteins and membranes during freezing and drying processes. This unique property of trehalose has made it a subject of attention in the field (Dermesonlouoglou et al., 2016). The use of polyols in OD offers the potential for producing healthier and safer dried snacks by preserving product quality during processing.

The influence of varying concentrations of polyols, specifically mannitol and sorbitol, on the kinetics of the OD process, as well as on various physical and chemical properties of organic strawberries, was assessed. The findings revealed that a 30% or 40% of sorbitol solution proved to be the optimal choice for OD. In comparison to a sucrose solution, sorbitol exhibited similar changes in bioactive chemicals and color properties. However, there was a noticeable shift in the sugar profile, marked by a reduction in sucrose, glucose, and fructose content, partially replaced by polyols (Wiktor et al., 2022). Sorbitol has the potential to serve as the ideal choice for OD of fruits, resulting in beneficial alterations in bioactive compounds and color properties, all while partially substituting natural sugars with polyols.

Maltitol, xylitol, and sucrose are identified as effective osmotic agents for dehydrating kiwiberries. Polyols, such as xylitol and maltitol, have demonstrated their efficiency as well as their reduced calorie content when compared to sucrose, a commonly used sweetener. This suggests that polyols can be employed as a healthier and more sustainable alternative in the OD of kiwiberries (Bialik et al., 2018). The influence of specific polyol compounds and other saccharides on the OD process of apples was investigated in a research study. By examining the kinetics of the process and comparing the results with those achieved using a sucrose solution, the efficacy of the OD procedure was assessed. Among the substances examined as solutions were erythritol, maltitol, xylitol, inulin, and oligofructose. The findings revealed that erythritol and xylitol performed as effectively as or even more effectively than sucrose in the OD process (Cichowska et al., 2018).

In another study, the potential of employing polyols such as erythritol, xylitol, and maltitol as alternatives to sucrose in the process of OD of apples was investigated. The research also determined the optimal concentrations of these sugars. The findings revealed that polyols exhibited similar or even superior efficiency compared to sucrose in the OD process. Notably, the degree of water loss exceeded that of solid gain by a factor of 2 to 10, regardless of the type of solution employed. Furthermore, minimal color variation was observed between fresh apples and those that underwent OD using solutions containing either sucrose or xylitol. This observation suggests that using xylitol as a replacement for sucrose in the OD process of apples could yield color outcomes similar to those achieved with sucrose. The study concluded that polyols, particularly erythritol, can be effectively utilized in the OD process to produce high-quality products without the addition of sugars (Kowalska et al., 2020b). The above-mentioned studies collectively demonstrate that maltitol, xylitol, and erythritol proved to be equally or even more efficient substitutes for sucrose in the OD process, thus potentially offering health-related advantages.

The osmotic properties of stained yogurt (SY) whey were investigated in the context of its potential use as an osmotic solvent for producing high-quality semi-dried or dried pumpkin products. The utilization of SY whey demonstrated enhanced mass transfer characteristics when compared to water as a solvent, resulting in a notable 20% increase in the diffusion coefficient for solid absorption. This outcome suggests that osmosis in SY whey solution is advantageous for solid enrichment from the osmotic solution, rendering it suitable for enhancing the solid content in various applications. Furthermore, the incorporation of specific substances with unique attributes, such as galacto-oligosaccharides (GOS), trehalose, and ascorbic acid, as osmotic solutes, holds the potential to create products with improved nutritional qualities. By utilizing these components, the overall nutritional value of the final product can be enhanced (Dermesonlouoglou et al., 2020).

Isomaltulose, also known as palatinose, has garnered considerable attention as a potential osmotic solute due to its distinctive characteristics. It boasts a low cariogenic index, promoting dental health, and a low glycemic index, which helps reduce glycemic spikes and insulin production. These attributes render isomaltulose an appealing option for individuals with specific dietary requirements, including athletes and diabetics. The utilization of isomaltulose in OD holds the potential to yield healthier and more sustainable products that cater to the needs of these target groups (Sawale et al., 2017).

7 Conclusion

The osmotic dehydration is a useful technique with numerous applications in fruits and vegetables. It is effectively employed to create mineral and water-soluble vitamin-enriched “snacks” from these produce items. This method is straightforward, simplifying the processing of fruits and vegetables, conserving energy, and allowing for the economical production of dehydrated products that retain their natural attributes while enhancing their nutritional value. The combination of diverse techniques, including vacuum assisted osmotic dehydration , sonication-assisted osmotic dehydration, and pulse electric field in combination with osmotic dehydration, demonstrates significant potential for increasing the nutritional content, microbial viability, and overall quality of various food products. These innovative methodologies offer promise for the food industry in the creation of more nutritious and appealing products. On a smaller scale, such as for home-based businesses and enterprises, implementing these processes can aid in reducing post-harvest losses, addressing nutritional deficiencies, and generating economic benefits for communities. The simplicity and efficiency of these processing techniques play a substantial role in elevating the quality of dried fruits and vegetables.

8 Future directions

Further research in utilizing osmotic dehydration as a fortification tool is necessary. Researchers can explore nanotechnology to achieve precise nutrient delivery in osmo-fortification, with the aim of enhancing bioavailability and ensuring controlled release. Exploring advanced encapsulation methods to safeguard delicate nutrients during osmotic dehydration is crucial.

Furthermore, studying the impact of osmo-fortification on the gut microbiome by incorporating prebiotics and probiotics is essential. Gaining insight into how osmo-fortified foods influence microbial communities holds promise for advancements in promoting gut health.

Additionally, continual refinement of osmo-combined techniques and collaboration with the food industry are vital for the practical application of these methods in the production of fortified snacks.

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