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Recent developments in osmotic dehydration of fruits and vegetables: A review

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Abstract
Osmotic dehydration is a process that involves the partial removal of water from fruits and vegetables. Multiple aspects that affect osmotic dehydration, including, the osmotic agent, duration and temperature, solute concentration, solution to sample ratio, agitation, and material geometry. Osmotic dehydration has recently been combined with several additional techniques, namely, ultrasound, high hydrostatic pressure, pulsed electric field, vacuum pulses and microwave *etc*. These strategies have been used to improve the performance by enhancing the permeability of the cell membrane and mass transfer rate during or after osmotic dehydration. These combined procedures minimize drying time and lowering energy costs. This paper presents the various aspects of the osmotic process as well as current breakthroughs in osmotic dehydration.

Keywords: osmotic dehydration, fruits and vegetables, recent trends, ultrasound, pulsed electric field, high hydrostatic pressure

Introduction
Fruits and vegetables are key sources of nutrients in the human diet and water makeup 75–95% of the fresh part of it. India is the world's second-largest producer of fruits and vegetables (Shete *et al*., 2018) [1]. The production of fruits and vegetables represents more than 30% of the agricultural Gross Domestic Product (GDP). However, these highly perishables are lost due to poor post-harvest handling and storage (Yadav & Singh, 2014) [2]. Many approaches have been invented to extend the storage life of fruits and vegetables. Drying and dehydration is a common procedure that is frequently used, due to significant cost savings in packaging, storage, and shipping weights *etc.*(Chavan &Amarowicz, 2012) [3].

Osmotic dehydration is one of the effective and appropriate method for extending the shelf life of fruits and vegetables. It is combined with dehydration and impregnation procedure. This dynamic mass transfer technique involves immersing food in hypertonic solutions of salt or sugar and producing two significant counter-current flows at the same time. During this process, water moves from the plant tissue into the osmotic solution, whereas osmotic solute diffuses from the solution to the tissue (Bellary *et al*., 2011) [4]. Osmotic dehydration is induced through osmosis. The difference in osmotic pressure between the plant tissue and its surrounding solution is the driving force for water removal. Meanwhile, tissue-specific solutes (sugars, organic acids, minerals, vitamins, and so on) are leached into the osmotic solution, although to a considerably lesser level than the first two transfers. Therefore, it is considered as a multi component transfer process (Bashir *et al*., 2020) [5].

In recent years, non-thermal techniques have received a lot of attention, due to high customer demand for nutritious, fresh foods, as well as the requirement for energy-efficient and environmentally friendly processing technologies (Oliveira *et al*., 2019) [6]. Techniques such as ultrasound, high pressure processing, pulsed electric field, vacuum pulses and microwave processing has been found to boost osmotic dehydration rate in several fruits and vegetables. It is utilised to enhance the functional, nutritional and sensory characteristics of food without compromising its structural integrity. Now a day's, osmotic dehydration is observed as an effective pre-treatment and food preservation strategy in the preparation of dehydrated foods. It has several other advantages, including decreasing heat damage to flavour and colour, suppressing enzyme browning, and lowering energy expenditures (Khan, 2012) [7]. The common solutes used in osmotic dehydration are sugar syrup with fruit slices or cubes and salt (sodium chloride) or brine with vegetables. Osmotic dehydration is influenced by several parameters, namely, osmotic agent, concentration of solute, agitation, temperature, immersion time, ratio of sample to solution, shape, size, and tissue compactness of the material (Bashir *et al*., 2020) [5].

Although the osmotic method does not provide a product with sufficient moisture content to be recognised as shelf stable, the osmosed product must be dried further, either by air, vacuum, or freeze drying (Chavan & Amarowicz, 2012) [3]. The use of osmosis in food processing is mainly for economic considerations and to improve the end product's quality. This idea varies from one food product to the next, depending on the product composition and structure (Akbarian *et al*., 2014) [8]. The present review focuses on factors that influence osmotic dehydration, packaging and storage of osmo-dehydrated products, its applications, and the recent advances in osmotic dehydration.

Brief history of osmotic dehydration

Osmotic dehydration of foods was first demonstrated by Pointing *et al*., (1966) [9] following this, tremendous studies have been conducted on osmotic dehydration. The drying rate of osmotic dehydration was represented by the apple monograph (Farkas & Lazor,1969) [10]. Osmotic dehydration methods were studied in sucrose and glucose solutions of fruits such as kiwi and papaya (Heng *et al*., 1990; Vial *et al*., 1991) [11, 12]. Mass transfer of pineapple through osmotic dehydration was examined by (Beristain *et al*., 1990) [13]. Torreggiani (1993) [14] investigated the sugar content, colour, acidity, vitamin C, pH, and organoleptic characters of osmotically processed cherries. Rastogi & Raghavarao (2004) [15] carried out real time experiments on mechanism and modelling of water loss and solid gain during osmotic dehydration of pineapple.

Principles of osmotic dehydration

Emerging innovative approaches have been thoroughly studied in terms of physico-chemical changes in the product during the dehydration process. Drying not only protects the product but it can also improve the quality of the materials which can develop value-added compounds during the drying process such as spices, medicinal plants, herbs, nuts, fruits and vegetables (Calin-sanchez,2021) [16]. Alzamora *et al*., (2005) [17] suggested that osmotic dehydration (osmotic treatment or dewatering impregnation soaking) appears to be a viable technology for the development of fruits and vegetable matrices to which functional ingredients can be successfully added, resulting in novel functional products and new commercial opportunities. The development of intermediate moisture food via osmotic dehydration has added a lot of attention from consumers in recent years due to its minimal processing (Ahmed *et al*., 2016) [18].

Osmotic dehydration is done by immersing foods such as fruits and vegetables in concentrated soluble solid solutions with higher osmotic pressure and lower water activity. The difference in the chemical potential of water between the food and the osmotic medium causes dehydration (Shete *et al*., 2018) [1]. During osmotic dehydration process, tissue shrinkage and mass transfer occur at the same time (Ahmed *et al*., 2016) [18]. Due to the complicated internal structure of food systems, achieving a full semi-permeable membrane is challenging and sometimes there is also solid diffusion into the food meaning that osmotic dehydration is a combination of water and solute diffusion processes (Chandra & Kumari, 2015) [19].

Bellary & Rastogi (2012) [20] viewed that the major advantage is to reduce the water activity of food materials, thereby inhibiting the growth of micro-organisms, since most of the food materials consist large amount of water;they are cost effective to storage and transportation. Osmotic dehydration is found to be an energy efficient method of partial dehydration process, since phase change is not needed. Other possibilities include food formulation by lowering the water activity and food fortification with compounds that can alter its structural, functional and nutritional properties. It is effective under room temperature so that heat damage to colour, texture, flavour also the loss of volatile component and oxidative changes could be minimized (Alzamora *et al*., 2005; Hasanuzzaman *et al*., 2014) [17, 21].

Mechanism of mass transfer through osmotic dehydration

Tiwari (2005) [22] reported that there are three forms of counter current mass transfer available for osmotic dehydration.

1. The flow of water from the material to the solution.
2. Absolute transfer from the solution to the product, allowing the required amount of an active principle such as a preservation agent, any solute, nutrient, or a sensory quality improvement of the product to be introduced.
3. Leaching out of a product's own solutes (sugar, organic acids, minerals, vitamins, and so on), which is little in comparison to the previous two forms of transfer but crucial in terms of the final product's composition.

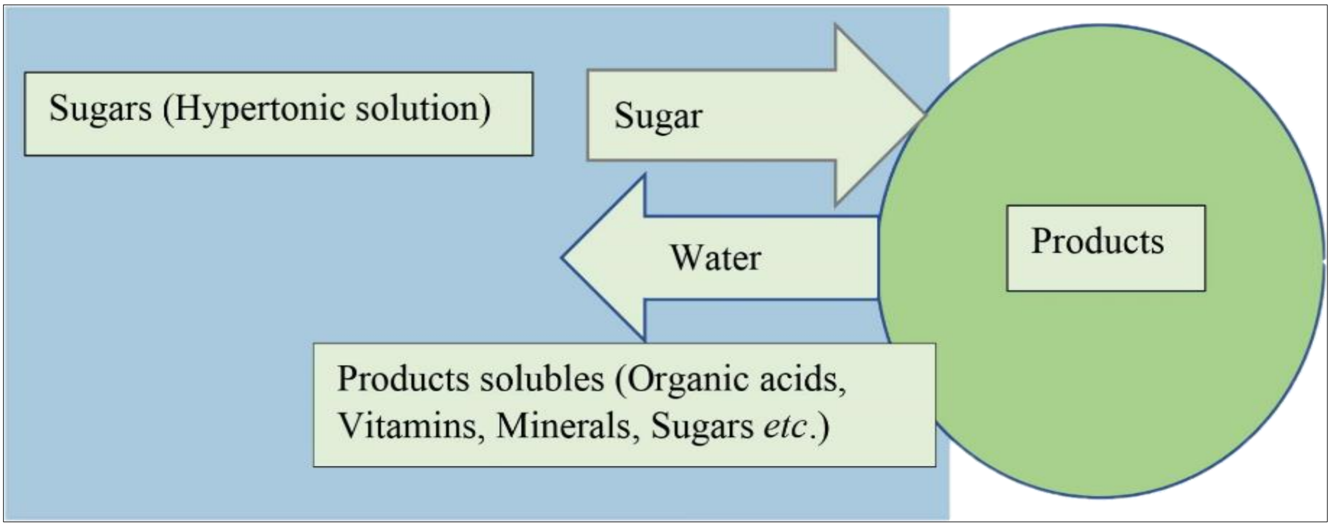

Fig 1: Schematic diagram of mechanism of osmotic dehydration

Osmotic process influencing parameters

Many factors that influence osmotic dehydration as a mass transfer process, including pre-treatment factors, product-related factors and osmotic solution-related factors. Terminologies like water loss, solids or solutes gain and weight reduction are used to explain the kinetics of mass transfer (Lenart & Lewicki, 2006) [23]. The effect of important process variables (osmotic solution concentration and composition, temperature and agitation of osmotic solution, duration of osmotic process, solution to sample ratio, pre-treatment, nature of the food products and its geometry, among others) on the mass transfer mechanism and product quality has been extensively studied for many fruits, including papaya (Jain *et al*., 2011) [24].

Pre-treatment methods

Ahmed *et al*., (2016) [18] examined that, if the membrane permeability is high, osmotic dehydration can occur more quickly. To prevent the detrimental changes in biological materials caused by typical drying procedures, many researchers have adopted pre-treatments such as blanching, sulphuring, alkaline dipping, high hydrostatic pressure and freezing prior to osmotic dehydration. To avoid enzymatic browning, fruits and vegetables were dipped in 1% citric acid solution before osmotic dehydration (Sunjka & Raghavan, 2004) [25]. Pre-treatments like blanching or use of sulphur dioxide can helps to prevent discoloration in fruits and vegetable. Mango and papaya slices were dipped in 0.4% ascorbic acid solution and 0.1% potassium metabisulfite + 0.4% ascorbic acid solution for 30 min before osmotic dehydration (Torreggiani, 1993) [14].

Osmotic agent

Osmotic dehydration is a process that combines dehydration and impregnation to lower the adverse effects of fresh food components. It is the process of partially reducing water from a substance by directly contacting it with a hypertonic medium such as a high concentration of sugar or salt solution for fruits and vegetables (Bellary & Rastogi, 2016) [26]. Ahmed *et al*., (2016) [18] reported that depending on the final product, many types of osmotic agents are utilised, such as glucose, corn syrup, sodium chloride, starch concentrates, fructose, and sucrose. Lopez *et al*., (2021) [27] pointed out that during osmotic dehydration, the osmotic agent plays a very important role as they effect the product's sensory and physical attributes. The most prevalent osmotic agent found in fruits is sucrose. Even though, the polyol solutions like inulin, maltitol, xylitol, erythritol and oligofructose showed similar or higher productivity as an appropriate substitute to sucrose solution.

In general, solutions made of sucrose are used to dehydrate fruits and sodium chloride is used to dehydrate vegetables. The force behind the drying process is increased with the incorporation of small quantities of sodium chloride to osmotic solution and explained the synergistic effects of sodium chloride and sucrose (Lerici *et al*., 1985) [28]. Normally, low molecular weight osmotic agents are more easily absorbed by fruit cells than high molecular weight osmotic agents. An osmotic agent or multiple osmotic agents can be used to treat osmotic dehydration. The osmotic agent needs to be practical, reliable, non-toxic, and delicious. It should be simple to dissolve and affordable to produce a highly concentrated solution that does not react with the material. Sugar and salt solutions found to be the best options in terms of efficacy, convenience, and taste (Tortoe, 2010) [29]. During the drying of osmotically treated products, sugar solution limits oxygen access, stabilises pigments and aids in the retention of volatile components (Pattanapa *et al*., 2010) [30]. Yadav & Singh (2014) [2] found that a combination of various osmotic agents was more efficient than sucrose alone.

Table 1: Different type of osmotic agents and their description

Osmotic agent	Description	Reference
Calcium chloride	During storage it improves the firmness and retain the texture of the fruit slices. Also prevents browning due to its synergistic effect with ascorbic acid or sulphur di oxide. The product would have a stronger flavour, if utilized at a concentration of more than 0.5 per cent.	Ponting (1973) [31]
Ethanol	The viscosity and freezing point of the osmotic solution are decreased during the de-hydro cooling process.	Biswal & Le Maguer (1989) [32]
Fructose	Sucrose is preferred because it has a higher rate of solute penetration than fructose. When compared to sucrose, it increases the dry matter content by 50% due to a higher penetration rate. The water activity of the finished product is slightly reduced. In contrast to fructose, sucrose is preferred.	Bolin *et al*., (1983) [33]
Invert sugar	At the same concentration, it is more efficient than sucrose, because when fully inverted, it has twice as many molecules per unit volume. The rate of osmotic dehydration is very slightly variable.	Ponting *et al*., (1966) [9]
Lactose	It is less sweet than sucrose. Also has a limited solubility in aqueous solution.	Hawkes & Flink (1978) [34]
Maltodextrin	Can be employed in a mixed system or at greater total solids concentrations.	Khin *et al*., (2007) [35]
Sodium chloride	This osmotic agent is extremely beneficial to vegetables. It helps to retard oxidation and thereby preventing enzymatic browning. The effects of bleaching on coloured materials can easily be minimised by combining salt and sugar. The rate of shrinkage is slowed, when the concentration is around 10%.	Hawkes & Flink (1978) [34]
Sucrose/sugar	Because of oxidative browning during osmosis, dry sugar is not acceptable. The sugar solution is the best, because it prevents browning by limiting oxygen from entering. Its sweetness restricts it from being used in vegetable processing.	Flink (1975) [36]
Starch/corn syrup	It favours a similar final water content as sucrose, with limited solid gain.	Flink (1975)[36]
Mixture of sucrose, salt, Invert sugar and salt, ethanol and salt	Because of the properties of both solutes, they are more effective than sucrose alone.	Lenart & Flink (1984) [37]

Concentration of osmotic solution

Phisut (2012) [38] observed that concentration of osmotic agent is an essential variable to impact the mass transfer kinetics during osmotic dehydration. As the concentration of the solution increased, the rate of osmosis was also observed to be faster. Rate of water loss and solid gain are improved by increasing the sucrose concentration during extended osmotic treatment. Water loss and solid gain ratios are reduced when sucrose solutions are less concentrated. In most circumstances, a syrup intensity of 60 to 70° Brix has been determined to be appropriate during osmotic dehydration (Tortoe, 2010) [29]. The mass transfer rate of apricot through osmotic treatment was reported by (Ispir & Torul, 2009) [39]. The apricot fruits were immersed in three different sugar concentrations (40%, 50% and 60%) the higher the osmotic pressure gradients, greater the sucrose concentration and hence higher will be the water loss and solid gain during the osmotic dehydration.

Lazarides & Mavroudis (1996) [40] studied the effect of sucrose concentrations (45, 55 and 65%) on osmotic dehydration of apples. They have found that high sucrose concentration resulted in more solid gain and water loss through the osmotic process. Mundada *et al*., (2011) [41] conducted an experiment on the effect of different sucrose concentrations (40°Brix, 50°Brix, and 60°Brix) on the mass transfer rate of pomegranate arils during osmotic dehydration. Pomegranate arils soaked in 60°Brix sucrose solution had more solid gain and water loss than those soaked in 40°Brix and 50°Brix osmotic solutions. In terms of water loss and solid gain, the concentration and temperature of the osmotic solution played a significant effect in improving mass transfer (Kaur *et al*., 2014) [42]. Bellary & Rastogi (2012) [20] investigated the impact of hypotonic and hypertonic solutions on curcuminoids impregnation in coconut slices. Due to the existence of endogenous soluble solutes, the rate of curcuminoid infusion into coconut slices was directly proportional to solution concentration as well as the osmotic pressure inside the solid food matrix.

Temperature of osmotic solution

Temperature is the most important kinetics parameter to take into account during osmotic dehydration. The rate of osmosis increased with temperature and it was limited to 60°C due to the damage to cell membranes caused by higher temperatures (Chavan & Amarowicz, 2012) [3]. Bera & Roy (2015) [43] conducted a study on effects of temperature on blue berries during osmotic dehydration. Temperatures exceeding 45°C can induce adverse colour, flavour and aroma changes as well as alterations in the cell wall of the food. The impact of temperature is more effective from 30 to 60 °C for fruits and vegetables on the kinetic rate of moisture loss without influencing solid gain. Temperature has less impact on solid gain. Water loss and solid gain increase as temperature rises up to 50°C. The osmotic equilibrium is established by the flow of water from the cell rather than by solid diffusion because water loss is stronger at higher temperatures. At temperatures above 50°C, it was noted that unfavourable alterations appeared on blue berries.

Duration of osmotic dehydration

The amount of water lost and the number of soluble solids gained is a function of time. Increased immersion time causes more moisture loss during osmotic dehydration (Ispir & Torul, 2009) [39]. The initial rate of osmosis is extremely high and had a considerable effect on continued growth of the osmotic process. In general, weight loss increases as treatment time goes on but the rate at which it happens lowers. The treatment period can be set so that the amount of water removed is as high as possible while no particulates are absorbed (Tortoe, 2010) [29].

While the solution's concentration remained unchanged, increasing the immersion period resulted in a slower rise in water loss. Reports on the effect of time on the osmotic process revealed that mass exchange happened at a faster pace within the first 2 h, followed by lowering the drying rate as processing time improved (Li &Ramaswamy, 2006) [44]. According to Tiwari & Jalali (2004) [45] during osmotic dehydration of mango and pineapple, higher osmotic duration resulted in increased weight loss. At a concentration of 45 to 60% and temperatures ranging from 20 to 50° C. Fernandes *et al*., (2006) [46] viewed that banana and apple slices dipped in to the sugar syrup concentration of 70 and 50°Brix respectively and osmotic solution temperature of 50° C for 3h immersion time offered optimum water loss and sugar gain.

Ratio of fruits to osmotic solution

As the solution-to-sample ratio rises, the rate of osmosis also increased. However, it is critical to utilise the best ratio possible because excessive ratios make processing of syrup fruit mixture harder. 1:2 or 1:3 ratio is best suitable for practical uses and ratios ranging from 1:1 to 1:5 is generally considered for mass transfer kinetics during osmotic dehydration. Raising the osmotic solution to sample mass ratio boosted both solid gain and water loss happened through osmotic dehydration (Akbarian *et al*., 2014) [8]. Some researchers utilised a significantly lower solution to product ratio (4:1 or 3:1) to trace mass transfer by following variations in the concentration of the sugar solution (Shete *et al*., 2018) [1].

Agitation of osmotic solution

When the syrup is stirred or circulated around the sample, osmotic dehydration rises. This is owing to lower surface mass transfer resistance. The lower rate of solid uptake caused by agitation over a longer osmosis duration could be an indirect impact of higher water loss. Therefore solute absorption into natural tissue is poor and the majority of the solute concentrated in to a thin sub-surface layer (Tortoe, 2010) [29]. Agitation or stirring can be used to improve mass transfer during osmotic dehydration. The use of highly concentrated viscous sugar solution causes a serious problem such as floating food particles impeding the interaction between food material and the osmotic solution resulted in to a reduction in mass transfer rates (Phisut, 2012) [38]. Throughout the osmotic process agitation has no direct effect on solid gain (Tortoe, 2010) [29].

Rastogi *et al*., (2002) [47] observed that agitation is one of the most important variables and an optimum amount of agitation guarantees that liquid-side mass transfer effects are minimised or eliminated. At low syrup concentrations gentle agitation has little influence on osmotic rate. Moreira *et al*., (2007) [48] investigated the effect of agitation and non – agitation methods. Compared to non-agitated samples, they have found that samples with agitation showed water loss and great weight reduce. In some of his reports he pointed that degree of agitation had a positive impact on water loss. During the dehydration process, agitation promotes turbulent flow which leads to an increase in liquid diffusion. In turbulent flow region water loss is greater when compared to laminar flow region.

Phisut, (2012) [38] suggested that agitation is a useful approach to increase mass transfer by minimising contact time and achieving improved moisture content in food components. Gupta etal., (2012) [49] used osmo-convective dehydration to develop a honey-ginger candy. According to the findings, the increased water loss and solute gain with soaking time and temperature was due to the agitation provided during osmotic dehydration process and lowered the mass transfer resistance between the surface of ginger and honey.

Application of osmotic dehydration process

Osmotic dehydration is primarily used to improve a product's nutritional, organoleptic and functional qualities. Process works at room temperature so that heat damage to colour, flavour is reduced and the sugar surrounding fruit and vegetable pieces is concentrated also preventing discoloration (Tortoe, 2010) [29]. Furthermore, high-quality fruits and vegetables with functional qualities suitable with various food systems are achieved through selective enrichment in soluble solids and lowered acidity with minimal or no use of sulphur di oxide. These benefits can be achieved with less energy than a standard drying procedure. Moreover, osmotic dehydration is a mild processing technique having better organoleptic affinity towards the natural and dehydrated products (Phisut, 2012) [38].

Benefits of osmotic dehydration

Tortoe (2010) [29] reported that osmotic dehydration can minimise the effect of temperature on food quality and retains the wholeness of the food. The organoleptic quality aspects such as colour, flavour and texture will be preserved during this process. Mild heat treatment promotes colour and flavour retention, giving the product exceptional organoleptic qualities, the effect is more when sugar syrup is employed as an osmotic agent (Chavan & Amarowicz, 2012) [3]. Osmotic dehydration is employed by continuous immersion of the food products in osmotic agents and therefore it can reduce O_2 exposure and hinder the activity of polyphenol oxidases thus preventing enzymatic browning and improves colour retention (Kaleemullah *et al*., 2002) [50].

Lazarides & Mavroudis (1996) [40] considered that osmotic dehydration process is an energy efficient method as compared to other dehydration techniques namely air, vacuum and tray drying as it can be conducted at low or ambient temperatures. It avoids the product's structural collapse during further drying also facilitates to retain the shape of the dehydrated products.

It is a simple and cost-effective method and the energy consumption is reduced by 2-3 times as compared to traditional drying. The technique minimises product volume, reducing storage and transportation costs (Bekele & Ramaswamy, 2010) [51]. The procedure could be useful in the manufacturing of ready-to-eat foods and thereby increase the storage life of the products developed (Zeeshan *et al*., 2016) [52].

Limitations of osmotic dehydration

Despite the benefits, the osmotic dehydration technique has some significant drawbacks. Yadav & Singh (2014) [2] suggested that the unique taste of osmotically dehydrated products is reduced as the acidity level is reduced. This can be avoided by including fruit acid into the solution. Sugar coating is undesirable in osmo dehydrated products and after treatment fast rinse in water may be required. Osmotic dehydration is a time consuming process and the dehydrated products is having high water activity. Chavan & Amarowicz (2012) [3] pointed out, osmotic treatment in combination with other techniques such as vacuum drying, air drying or blanching was found to be costly.

Packaging and storage of osmo-dehydrated products

Airtight packaging can be used to store osmotically dehydrated products to avoid absorption of humidity from the environment as well as degradation caused by infestation. Polypropylene bags (laminated) and aluminium foils are the perfect packaging materials for osmotically treated products (Sagar & Khurdiya,1999) [53]. Ahmed & Choudhary (1995) [54] used high-density polyethylene bags as a packaging material for osmo-dried papaya fruit and stored at a constant temperature for a period of six months or so, with minor changes acceptable.

The microbiological load of products developed by osmotic dehydration is a significant problem for their shelf life particularly in the cut fruits and the strategy for lowering microbial load could minimize postharvest losses and hence creating value to food items (Castello *et al*., 2009) [55]. Prothon & Ahrne (2004) [56] revealed that microorganism require different quantities of water activity to survive. It is a critical component of the shelf life of the products developed through osmotic dehydration.

An appropriate mix of water activity and pH was found effective for limiting microorganisms in food products (Tiganitas *et al*., 2009) [57]. Jose *et al*., (2011) [58] conducted an experiment on osmotic dehydration of pineapple and optimized the citric acid concentration (0.5% - 2.5% w/w) and temperature (25- 45 °C) with a greater reduction in microbial count and better sensory acceptance.

Ahmed & Choudhary (1995) [54] reported that the storage stability of osmotically dehydrated papaya and maintained its consistency up to six months when stored at room temperature. Banana products that have been osmotically dehydrated can be stored up to a year or longer depending on the storage conditions, temperature, and packaging materials utilised (Bongirwar & Sreenivasan, 1977) [59].

Advancements in osmotic dehydration

Osmotic dehydration is a time-consuming procedure especially when applied at room temperature because osmotic pressure is the only driving force for mass transfer. Due to this, a number of combinations of osmotic process with other conventional and novel techniques has lately been investigated (Ahmed *et al*., 2016) [18]. Ultrasound, high hydrostatic pressure, pulsed electric field, vacuum pulses and microwave are some of the combination treatments that can improve mass transfer by enhancing the efficiency of the process and also by increasing the quality of the final product (Amami *et al*., 2017) [60].

Ultrasound assisted osmotic dehydration

Many researchers has shown interest on ultrasound usage in the osmotic process because it can be used as a pre-treatment or as an ultrasound assisted osmotic dehydration (Małgorzata *et al*., 2021) [61]. Li *et al*., (2020) [62] pointed out that ultrasound has long been utilised as a pre-treatment for the drying of fruits and vegetables. Ultrasound waves can generate a series of alternate compressions and expansions in connection with osmotic dehydration moreover low frequency ultrasound waves found to be appropriate for fruits and vegetables. The sonication effect creates bubbles in the osmotic solution. It has the potential to explode and create localised pressure that may facilitate in the removal of the water content of fruits and vegetables (Ahmad & Zaidi, 2020) [63].

Rahaman *et al*., (2019) [64] investigated the application of ultrasound during osmotic dehydration using 50% glucose and sucrose for 30 and 60 min enhances water loss and solid gain in the plum. Another study on ultrasound based osmotic treatment of kiwi fruit was reported by (Prithani & Dash, 2020) [65]. To produce a stable intermediate moisture product with appreciable nutrient composition and sensory qualities, a combination of ultrasound pre-treatment and osmotic dehydration could be utilised and the product can be used itself as a dried fruit or as an addition with other processed food products.

Pulsed electric field assisted osmotic dehydration

Yu *et al*., (2017) [66] observed that the mass transfer during osmotic dehydration of blue berry was improved by the application of pulsed electric field treatment. Oliveira *et al*., (2019) [6] also reported the mass transfer and energy efficiency of pulsed electric field assisted osmotic dehydration of strawberries. Barba *et al*., (2015) [67] pointed out pulsed electric field assisted osmotic dehydration can inhibit certain enzymes and this will help in the colour retention of fruits and vegetables. The application of pulsed electric field pre-treatment prior to osmotic dehydration of fruits like kiwi and strawberry revealed that in terms of mass transfer the combined procedure increased the dehydration rate of both fruits correspondingly to the applied electric field strength. In strawberries solid gain remained unchanged, however, decreased in kiwifruit (Tylewicz *et al*., 2020) [68].

High hydrostatic pressure assisted osmotic dehydration

Luo *et al*., (2019) [69] conducted a study on use of high pressure as a pre-treatment during osmotic dehydration of wumei fruit (*Prunus mume*) reported that mass transfer is accelerated when compared to the traditional heating treatment. High pressure processing yielded a potential approach for making candied wumei fruit with excellent nutritional and sensory properties. Dash *et al*., (2019) [70] investigated the use of high pressure during osmotic dehydration of ginger slices reported the improved kinetics of water loss and solid gain and obtained the higher quality products with reduced drying time and energy expenditure.

According to (Nunez-Mancilla *et al*., 2013) [71] during osmotic dehydration the strawberry samples treated at a high pressure of 400 MPa for 10 min maintained vitamin C content and had a high level of nutrients and antioxidant capacity. Likewise, pre-treatment with high pressure improved mass transfer in banana slices (Verma *et al*., 2014) [72].

Pulsed vacuum osmotic dehydration

A study was conducted on factors influencing mass transfer during osmotic dehydration of autumn olive berry (*Elaeagnus umbellata*) at atmospheric pressure and under vacuum. In autumn olive berries the vacuum application resulted in the increase of general characteristics of the final product (Ghellam *et al*., 2021) [73]. Reports showed that, the decrease in pressure caused by the vacuum pulses allows the air in the intercellular spaces and pores of the fruits and vegetables to expand, expelling it by hydrodynamic mechanisms mediated by the pressure difference and thus increasing the surface area accessible for mass transfer (Correa *et al*., 2010; Junqueira *et al*., 2017) [74, 75].

It has been found that using a vacuum at the start of the osmotic process enhances water loss and the solute gain in fruits and vegetables (Correa *et al*., 2016) [76]. During osmotic dehydration, the water loss and solid gain of garlic slices were significantly affected by the use of ultrasonic and pulsed vacuum technologies. This advanced method improved the rate of mass transfer during the osmotic dehydration of garlic slices compared to conventional osmotic process (Feng *et al*., 2019) [77].

Microwave assisted osmotic dehydration

Microwave energy can be coupled with osmotic dehydration to get quick and even heating and thus significantly reducing drying time and improving solute uptake by varying the dielectric characteristics (Ekezie *et al*., 2017) [78]. The effect of microwave-vacuum pre- treatment on osmotic dehydration of whole cranberries was demonstrated by (Zielinska & Markowski, 2018) [79]. Concluded that mass transfer is greatly increased by the pre-treatment applied. Compared to traditional osmotic dehydration the use of microwave pre-treatment combination with osmotic dehydration by maintaining a constant temperature exhibited some potential benefits on dehydration kinetics and qualitative attributes of apple cubes, such as enhanced moisture loss and decreased solid gain. So that it can be used for the developments of dried products with limited calories and reduced sugar content helpful for people suffering from diabetes (Manzoor *et al*., 2021) [80].

Patel & Sutar (2016) [81] used a pulsed-microwave-vacuum osmotic drying for elephant foot yam slices. This combination yielded yam slices of good quality with low moisture content. As a result, combining osmotic process with microwave aided air drying provides better process control and product quality, among other advantages (Ekezie *et al*., 2017) [78].

Table 2: Osmotic dehydration of fruits and vegetables with the assistance of non-thermal technologies

Fruits and Vegetables	Technology applied	Reference
Kiwifruit	Ultrasound	Prithani & Dash (2020) [65]
Apple	Ultrasound	Ma *et al*., (2021) [82]
Kiwifruit	Ultrasound	Roueita *et al*., (2020) [83]
Plum	Ultrasound	Rahaman *et al*., (2019) [64]
Apricot	Ultrasound	Sakooei-Vayghanet *et al*., (2020) [84]
Sweet potatoes	Ultrasound	Rashid *et al*., (2020) [85]
Pomegranate seeds	Ultrasound	Bchir *et al*., (2020) [86]
Sweet lime	Ultrasound	Kumari *et al*., (2020) [87]
Sweet potatoes	Ultrasound	Oladejo *et al*., (2017) [88]
Sour cherries	Ultrasound	Siucinska *et al*., (2016) [89]
Sweet potatoes	Ultrasound	Oladejo & Ma (2016) [90]
Strawberry	Ultrasound	Amami *et al*., (2017) [60]
Cranberries	Ultrasound	Nowacka *et al*., (2018) [91]
Cranberries	Ultrasound	Nowacka *et al*., (2019) [92]
Carrot	Ultrasound	Nowacka & Wedzik (2016) [93]
Pomegranate arils	Ultrasound	Allahdad *et al*., (2019) [94]
Mango	Ultrasound	Fernandes *et al*., (2019) [95]
Kiwi fruit	Ultrasound	Nowacka *et al*., (2017) [96]
Pumpkin slices	Ultrasound	Caglayan & Barutcu Mazı, (2018) [97]
Blueberries	Ultrasound	Spinei & Oroian (2021) [98]
Kiwi fruit	Ultrasound	Kroehnke *et al*., (2021) [99]
Mushroom	Ultrasound & Pulsed electric field	Dellarosa *et al*., (2017) [100]
Apple	Pulsed electric field	Parniakov *et al*., (2016) [101]
Kiwi, Strawberry	Pulsed electric field	Tylewicz *et al*., (2020) [68]
Goji berry	Pulsed electric field	Dermesonlouoglou *et al*., (2018) [102]
Apple	Pulsed electric field	Dellarosa *et al*., (2016) [103]
Blueberries	Pulsed electric field	Yu *et al*. (2017) [66]
Blueberries	Pulsed electric field	Yu *et al*., (2018) [104]
Strawberries	Pulsed electric field	Oliveira *et al*., (2019) [6]
Wumei fruit	High pressure processing	Luo *et al*., (2019) [69]
Ginger slices	High pressure processing	Dash *et al*., (2019) [70]
Carrot	Ultrasound &Vacuum pulses	Alizehi *et al*., (2020) [105]
Garlic slices	Ultrasound & Vacuum pulses	Alolga *et al*., (2021) [106]
Garlic slices	Ultrasound & Vacuum pulses	Feng *et al*., (2019) [77]
Apple slices	Vacuum pulses	Amanor-Atiemoh *et al*., (2020) [107]
Autumn berry	Vacuum pulses	Ghellam *et al*., (2021) [73]
Egg plant slices	Vacuum pulses	Junqueira *et al*., (2017) [75]
Tomato	Vacuum pulses	Correa *et al*., (2016) [76]
Figs	Vacuum pulses	Sahin & Ozturk (2016) [108]
Apple cubes	Microwave	Manzoor *et al*., (2021) [80]
Cranberries	Microwave, Vacuum pulses & Ultrasound	Zielinska & Markowski (2018) [79]
Elephant foot yam	Microwave & Vacuum pulses	Patel & Sutar (2016) [81]
Fresh berries	Microwave	Wray & Ramaswamy (2015) [109]
Apple	Microwave, Ultrasound& Vacuum pulses	Masztalerz *et al*., (2020) [110]

Future prospects of osmotic dehydration

Osmotic dehydration offers only minimal thermal degradation to the product due to the low-temperature moisture removal process. Though it is an old technology, even now it is practiced with some modifications to improve the solute-solvent mass transport phenomena. Moreover, osmosis is widely adopted technology for the separation of solvent and solute in the food industry, waste water treatment, medicine, allopathy, *etc*. on a commercial basis. Considering its low energy-intensive nature, osmotic dehydration has a huge potential to preserve food in a cost-effective manner. Opportunities for the improvements with enhanced efficiency of the osmotic dehydration largely revolves on studies on pre-treatments given to the biological sample, and coupling this technique with other effective drying methods. Osmotic dehydration coupled with conventional and novel techniques like ultrasound, high hydrostatic pressure, pulsed electric field, vacuum and microwave, will open up a new era of minimally processed and naturally preserved food products without the loss of nutrient quality. However, technological challenges like loss of product sensory quality, syrup management for repeated use, inadequate information regarding proper process control and design need to be addressed for better expansion of the utility horizon of osmotic dehydration.

Conclusion

Osmotic dehydration is one of the most important food preservation techniques in the processing of dried foods and can successfully reduce the weight of a substance by 50% and needs to be dried or processed to extend its shelf life. Osmotic dehydration is a procedure for conserving energy and improving quality. This is because it has several advantages including retention of nutrients, colour, flavour and texture of the product. Factors affecting osmotic dehydration such as osmotic agents, temperature, processing time, agitation and pre-treatments play significant impact on mass transfer kinetics. Recently, non-thermal methods have been developed to enhance mass transfer without adversely affecting quality of the food products. These techniques include the use of ultrasound, high hydrostatic pressure, pulsed electric field, vacuum pulses and microwave.

The combination of emerging techniques with traditional osmotic process is a viable alternative with high productivity and with minimal effects on food quality attributes. These benefits may open the way for the development of extremely desired food products for consumers as well as a greater adoption of non-thermal technologies on a commercial basis. The process of osmotic dehydration adds value to the end product making it safe, nutritious and available throughout the year. On the other hand, since there is no added preservative, the technique is extremely cost-effective and has no side effects on the human body.

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