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Review

Innovative technologies for producing and preserving intermediate moisture foods: A review

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ABSTRACT

Intermediate moisture foods (IMF) or semi-dried foods (SDF) have gained more attention worldwide having features very similar to fresh food products, but with a longer shelf life. This review presents the recent developments in novel technologies and methods for the production and preservation of IMF. These include new drying methods, using agents to reduce water-activity, innovative osmotic dehydration technologies, electro-osmotic dewatering, thermal pasteurization, plasma treatments (PT), high pressure processing (HPP), modified atmosphere packaging (MAP), edible coating, active packaging (and energy efficiency, improve quality and extend the shelf life of the final food AP) and hurdle technologies (HT). Innovative methods applied to producing and preserving IMF can enhance both drying products. Yet more systematic research is still needed to bridge knowledge gaps, in particular on inactivation kinetics and mechanisms related to thermal and non-thermal pasteurization technologies for control of pathogens and spoilage micro-organisms in IMF.

1. Introduction

Fresh foods, such as fruits, vegetables, meat and aquatic products, are important sources of human diet. Most of the fresh foods are perishable because of their high moisture content. Both free water and bound water exist in those food materials. Free water is the solvent for chemical/biochemical reactions and microbial growth while bound water makes up the structure of cells and organisms of raw materials. Water activity (a_w), defined as the ratio of partial water vapor pressure of a food vs the vapor pressure of pure water, is a measure of water mobility; higher a_w value indicates that more free water in the food can be utilized by microorganism and chemical/biochemical reactions. Food spoilage depends on intrinsic and extrinsic factors among which a_w and temperature play a significant role (Dagnas, Gougouli, Onno, Koutsoumanis, & Membré, 2017). Microbial growth and endogenous enzyme catalysis are two crucial mechanisms through which food items are spoiled, both rely on availability of free water (Maneffa et al., 2017). Dried foods can be stored for a long period, but their nutritional and sensory characteristics are often lost along with the removal of water during conventional industrial dehydration processes which often take long time at elevated temperatures. Improper use of the preservation methods after dehydration may create food safety risks, quality deterioration, and a short product shelf life.

IMF or SDF typically contain 20 to 50 weight-% [*w*/w] moisture content. The a_w of IMF is between 0.70 and 0.85 (Vermeulen, Daelman, Van, & Devlieghere, 2012), and the products are generally considered as microbiologically stable at room temperature (Vermeulen et al., 2015). In general, IMF maintain some certain initial characteristics (color, texture and flavor) of fresh food products. The unique features that make IMF appeal to consumers include conceived microbial safety,

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Abbreviations: AP, Active packaging; a_w, Water activity; CMIHA, Combined mid-infrared and hot air; CO_2, Carbon dioxide; FD, Freeze drying; FIVD, Far-infrared vacuum drying; HPP, High pressure processing; IF, Infrared drying; IM, intermediate moisture; IMF, Intermediate moisture foods; MAFD, Microwave assisted freeze drying; MAHD, Microwave-assisted hot air drying; MAOD, Microwave assisted osmotic dehydration; MAP, Modified atmosphere packaging; N_2, Nitrogen; OD, Osmotic dehydration; O_2, Oxygen; PSBMFD, pulse-spouted bed microwave freeze drying; PSMVD, pulse-spouted microwave-assisted vacuum drying; PT, Plasma treatment; RTE, Ready to eat; SDF, Semi-dried foods; UAOD, ultrasound assisted osmotic dehydration; VMD, Vacuum microwave drying; VI, Vacuum impregnation

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desirable odors, high nutritional values, ready to eat (RTE) (Carla, Rosaria, Antonio, Antonio, & Roma, 2010).

Production of IMF with properties close to fresh foods yet having extended the shelf life to satisfy the demand of the consumer is vitally important for the food industry. Drying is an important step to reduce water in IMF. Hot air drying is one of the most commonly used drying methods, because of low cost and simple operation. Hot air drying has been used for production of a wide range of products, including Chinese jujube (Fang, Wang, Hu, & Ashimk, 2009), grape (Adiletta et al., 2015) and semi-dried cherry tomatoes (Rizzo, Clifford, Brown, Siracusa, & Muratore, 2016). But hot air drying suffers from several deficiencies such as low energy efficiency, long drying time (Liu et al., 2016), and often poor product quality. For example, it was found that intermediate moisture (IM) beef dried by hot air have off-flavors and tough texture (Speckhahn, Srzednicki, Desai, & Devahastin, 2010). Microwave combined with vacuum drying was then used to facilitate drying of IMF such as shrimps (Lin, Durance, & Scaman, 1999), carp (Zhang, Min, Liang, & Fang, 2007) and so on. For this reason, novel and innovative technologies are increasingly explored for production of IMF.

Water-activity-lowering agents are widely used to prepare fruits, vegetables or meat products of immediate moisture contents for extended shelf life (Finn et al., 2015; Schmidt, Bam, & Laurindo, 2008). Conventional water-activity-lowering agents include salt and phosphates. However, it was also demonstrated that some of those effective conventional water-activity-lowering agents were expensive and usually influenced the flavor of IMF while providing no nutritional benefits. In addition, they need to be labeled, overuse may be harmful to human health (Torti, Sims, Adams, and Sarnoski, 2016, b). It is important to select suitable water-activity-lowering agents within an acceptable concentration to avoid their influence on the flavor of food products. Recently many research efforts have been concentrated on the water-activity-lowering agents to solve these problems, among which application of the combination of water-activity lowering-agents is the most promising (Tenhet, Finne, & Toloday, 1981).

Osmotic dehydration (OD) is another effective traditional method to reduce the amount of water in fresh foods in preparation of IMF. Glucose, salt, sucrose, glycerol, sorbitol, corn syrup, glucose syrup and fructo-oligosaccharides are commonly used osmotic agents (Tortoe, 2010). Osmotic agents should be carefully selected for different food materials. For example, salt is used for vegetable processing. But because of its salty taste, it is not widely applied to the dehydration of fruit (Phongsomboon & Intipunya, 2009). Sucrose has commonly been used as osmotic agent for fruit (Pattanapa, Therdthai, Chantrapornchai, & Zhou, 2010). Osmotic agents such as honey, ethanol, high fructose corn syrup and maple syrup are receiving considerable attention due to their high dehydration rates, good rehydration properties, and little damage to texture of food products. It is reported that dried apple slices dehydrated by 30–40% maple syrup processed the lightest color and best textural properties compared to other sugars (Rupasinghe, Handunkutti, Joshi, and Pitts, 2010).

OD partially removes water from food products, leading to minimally processed food of high quality with a relative long shelf life (Silva, Fernandes, & Mauro, 2014). The major driving force of OD is the difference between the osmotic pressure of the hypertonic solution and that if the cells in the food matrices. However, a major disadvantage is that OD takes a long time which may cause partial quality degradation in some products (Zhao, Hu, Xiao, Yang, Liu, Gan, and Ni, 2014a, b). Novel technologies have been explored to overcome these disadvantages. Among these are microwave assisted osmotic dehydration (MAOD), vacuum impregnation (VI), ultrasound assisted osmotic dehydration (UAOD) and osmodehydro-freezing.

IMF with a water activity between 0.70 and 0.85 do not support growth of bacterial pathogens. Mold and yeast may still grow. Recent outbreaks caused by salmonella in low moisture environment have caused food safety concerns for both low moisture foods and IMF (Syamaladevi, et al., 2016). Thermal pasteurization can play an important role in extending the shelf life and ensure microbial safety of IMF, it has been increasing applied on packed IMF in recent years. But heat sensitive components of IMF may be destroyed by thermal processing. With the rapid development of contamination technologies over the past few decades, particular attention has been paid to novel non-thermal contamination techniques to solve the problem above, including the uses of HPP and CP.

The increasing demand for shelf stable IMF accelerating the development of package methods. In order to protect consumers from food-borne diseases, microbial inhibition has been an important consideration in new package developments. Long shelf life can be achieved by modified atmosphere packaging (MAP) and active packaging (AP) through changing the ratio of gases composition in the package made from semipermeable materials or by incorporating chemical substances. Edible coating can extend the shelf life of foods by using edible antibacterial material directly coated on the surface of IMF. The coating also serves as a barrier to oxygen (O_2) and water.

The application of hurdle technology is another useful technique that combines two or more hurdles to achieve the maximum lethality against microorganisms, while minimizing the effects on sensory qualities.

To the best of our knowledge, there is no critical and systematic review of availability, applicability, advantages and disadvantages of innovative technologies applied to IMF. This work reviews currently available up to date technologies that are used for producing and preserving IMF.

2. Novel technologies for producing IMF

2.1. Innovative drying techniques

Fresh foods with high moisture content are vulnerable to quality degradation due to high levels of bio-chemical reactions and microbial growth during post-harvest storage (Zhang et al., 2007). Drying is an effective method to remove water from those foods. Traditional drying methods (i.e., hot air drying, sun drying, vacuum drying, freezing drying) have drawbacks such as long drying times, high energy consumption, and possibilities of causing sharp changes in product sensory and nutritional quality (Aneta Wojdyło, Figiel, Lech, Nowicka, & Oszmiański, 2014). Numerous efforts have been made to find novel and economic drying methods which could reduce the moisture content of food materials while maintain nutritional and physicochemical properties of the products. For example, different drying methods were evaluated on lipid deterioration, color changes and oxidation of semi-dried tilapia (Chaijan, Panpipat, & Nisoa, 2016). The samples dried by microwave drying displayed lower degree of lipid oxidation and higher protein carbonyl content than sun dried products. Novel and combined drying methods offer various merits over conventional ones and should be widely investigated to improve drying processes.

2.1.1. Microwave drying and combined microware drying

Microwave generates heat from the inner part of food materials through dipolar rotation and ionic movement. Higher vapor pressure is generated from the inner part and then to the surface of food materials through internal pressure gradient in a drying process. Microwave drying and combined microwave drying commonly consist of three characteristic drying periods: (1) heating period during which product temperature increases sharply to the point of water evaporation, (2) rapid drying period characterized by a high moisture evaporation rate driven by internal vapor pressure and (3) falling drying rate period resulted from continuously reduced moisture evaporation rate due to reduction in the absorption of microwave. Microwave drying increases the drying efficiency by concentrating the heating process within the material and while transferring moisture through the material under a high internal vapor pressure (Annie, Chandramouli, Anthonysamy, Ghosh, & Divakar, 2017). However, there are also limitations associated with microwave drying. These include uneven heating, limited penetration depth of the microwaves, and possible damage of texture when product temperature rises too high. Proper microwave power control and combination with other drying methods must be carefully considered to overcome those drawbacks.

Energy efficiency has been a major consideration in several reported studies. Microwave drying was considered as an energy efficient method. In a research on microwave drying of Chinese, Wang, Fang, and Hu (2009) reported that microwave drying led to effective diffusivity and less energy consumption when controlled at a proper microwave power level. In another studies, it was reported that the energy efficiency of apples slices dried by microwave was 54.34% at 600 W of microwave power and 17.42% at 200 W (Zarein, Samadi, & Ghobadian 2015). But drying time increased with the reduction of microwave power; there is thus a need to assess optimum process conditions. Darvishi, Azadbakht, Rezaeiasl, and Farhang (2013) studied energy consumption of microwave drying for sardine fish at different microwave power levels (200, 300, 400 and 500 W). It was found that microwave drying significantly decreased the drying time, from 9.5 to 4.25 min, with the increase of microwave power input. As compared with hot air drying alone, microwave-assisted hot air drying (MAHD) can reduce energy consumption by up to 55%. Higher retention of vitamin C and less browning of Chinese jujube was achieved by MAHD compared to using hot air drying alone (Fang et al., 2011b). MAHD has been studied for various IMF such as crude olive cake (Çelen, Aktaş, Karabeyoğlu, & Akyildiz, 2016), bread (Holtz, Ahrné, Rittenauer, & Rasmuson, 2010) and sausage (Guo, Xiong, Song, & Liu, 2014) to reduce energy consumption and improve product quality.

Vacuum microwave drying (VMD) is also a promising drying method with low cost, high drying efficiency and good product quality. VMD can preserve more color and reduce toughness of strawberries after drying (Bruijn et al., 2015). VMD holds unique advantages in reducing oxidation of nutrients in chicken fillets compared to conventional methods. For example, Wojdyło et al. (2016) reported that freeze drying (FD) and VMD are the best drying methods for jujube fruits. However, the price of FD is higher, so VMD is the most suitable drying method. Que (2013) also found VMD suitable for the drying of hairtail fish meat gel with little adverse effect on the quality. Pulse-spouted microwave-assisted vacuum drying (PSMVD) (Askari, Emam-Djomeh, & Mousavi, 2013), pulse-spouted bed microwave freeze drying (PSBMFD) (Wang et al., 2014) and Microwave assisted freeze drying (MAFD) (Wang, Zhang, Wang, & Martynenko, 2018) were also studied for understanding their suitability for diced apples. The quality of fish granules dried by vacuum drying (VD), VMD, and PSVMD were compared by Zhang et al. (2014). They found that the samples dried by PSVMD (6 W/g) displayed optimal quality compared to the samples by the other methods.

FD can be combined with VMD. It is reported that FD combined with VMD can reduce the time of FD alone to 40%, while the nutritional quality of the dried apple remained unchanged (Huang, Zhang, Mujumdar, & Wang, 2014). PSBMFD was applied to the production of apple cuboids. Premium quality apple cuboids with natural apple color and volatile compounds can be produced by PSBMFD (Wang et al., 2018).

2.1.2. *Infrared drying and combined infrared drying*

Infrared drying delivers energy to products via electromagnetic waves having wavelengths between 0.75 and 1000 μm (Riadh, Ahmad, Marhaban, & Soh, 2015). The infrared radiation is absorbed directly by food materials without heating the environment. Attractive features of infrared drying include higher rate of dehydration, efficient conversion of energy, higher speed of shutting down, starting up of the drying procedure and lower cost (Jangam, 2016). Infrared drying has been applied to the drying process of beef jerky with enhanced drying rate as compared to hot air drying (Li, Xie, Zhang, Zhen, & Jia, 2017). Infrared drying was also applied to drying pork slices with increased drying rates which were affected by drying temperature, slice thickness and initial moisture content of the pork slices (Ling, Teng, Lin, & Wen, 2017). When using for the dehydration of stale bread, the drying time was shortened by up to 69% and energy consumption was reduced by 43.2%, compared to conventional heat pump drying (Aktaş, Şevik, & Aktekeli, 2016). Infrared drying can be easily combined with other traditional drying methods for industrial applications. The jerky dried by combined mid-infrared and hot air (CMIHA) had better quality, the drying rate was higher than hot air and mid-infrared drying alone (Xie et al., 2013). Mee-Ngern, Lee, Choachamnan, and Boonsupthip (2014) optimized the far-infrared vacuum drying (FIVD) of preserved mango to improve the quality and shorten the drying time. The combination of microwave and infrared drying has also been applied to improve the quality parameters of cakes. The quality parameters of the final products were significantly enhanced by the combined drying methods (Ozkahraman, Sumnu, & Sahin, 2016). Infared drying was also combined with microwaves to improve the drying rate while improving the quality of beef jerky (Wang, Pang, Wang, & Xiao-Bo, 2012).

In spite of the advantages microwave drying and infrared drying brought in terms of high drying rate, energy efficiency and high product quality, several drawbacks (uneven heating and limited penetration depth) have hindered the widespread of those new technologies (Su et al., 2015). Drying technologies should be carefully selected according to the kind of the food products. Examples about drying methods for IMF and their advantages and disadvantages are listed in Table 1.

2.2. *Water-activity-lowering agents*

IMF can be produced by adding water-activity-lowering agents to reduce the amount and mobility of water, and accordingly lower a_w. Lowing a_w prevents or hinders the growth of foodborne pathogens and prolong the shelf life. In general the stability of IMF positively is correlated with reduced a_w (Beuchat et al., 2013). Adding water-activity-lowering agents such as salt, organic acids can maintain relatively high water contents with low a_w, thus reducing much loss of food flavor. Different water-activity-lowering agents can be used alone or in combination to achieve higher dewatering rate, better quality, and longer shelf life. Examples about the application of water-activity-lowering agents are listed in Table 2.

2.2.1. *Combination of different water-activity-lowering agents*

Single humectant may have an intensive impact on the flavor of food products. For example, too much salt may crease the intensity of saltiness and affect the flavor of the food products. The quality characteristics of semi-dried jerky made by dehydration using a combination of sucrose and sugar alcohols (sorbitol, glycerol and xylitol) was better than the products dehydrated with sucrose alone (Jang et al., 2015). Many researchers have clearly demonstrated that the combination of different water-activity-lowering agents is more effective in preserving the quality of food products than using single agent. Optimal combinations of water-activity-lowering agents have been studied by several researchers to produce high quality IMF. For example, Cui, Xue, Xue, Wei, Li, and Cong (2013) found that phosphate of 0.22%, sorbitol of 3.12% and glycerol of 2.51% were the optimal condition to obtain the lowest a_w of 0.884 in shelf-stable, RTE shrimps. The final samples had a longer shelf life and higher sensorial acceptability compared to the controls (without adding water-activity-lowering agents). Similarly, Thippeswamy, Venkateshaiah, and Patil (2011) reduced a_w of paneer to 0.970 by adding a combination of 3% NaCl, 0.1% citric acid and 0.1% potassium sorbate. The shelf life of samples packaged by MAP of which the ratio of the gas composition was 50% carbon dioxide (CO_2) and 50% nitrogen (N_2) can be extended by 11 and 14 days at 30 ± 1 °C and at 7 ± 1 °C, respectively, without losing much sensory and physicochemical characteristics. Water-activity-lowering agents have also been applied to smoked sausages (Ahlawat, 2012), pesto sauce (Carla, Mariarosaria, Antonio, Antonio, & Roma, 2008), *Brassica parachinensis*

Table 1
Application advantages and disadvantages of drying methods.

References	Fang (2011a)	Saavedra (2015)	Li (2018)	Xie (2014)	Cumhur (2015)	Hill (2014)	Chen (2014)	Zhang (2016)	Therdthai (2016)	Sebastia (2015)
Disadvantages	Carefully selection of drying temperature and microwave power for different raw materials	Slight change of color	Limited penetration depth Unsuitable for thick food materials.	Difficult dehydration of bound water	High operating costs	Lower rehydration capacity in cooked samples	Numerous pretests	Significant changes of structure and rheological properties	High hardness and enthalpy of retrogradation	Demand for drying pretreatment step
Advantages	Low energy consumption High product quality	Less energy consumption and drying time Higher quality (less color loss and more elastic)	High dehydration rate Low energy consumption	High product quality High drying rate	Establishment of a dynamic model high quality	lower hardness and higher elasticity of dried cooked samples	optimal quality at the microwave power of 6 W/g less drying time	Short drying time Easy operation	Production gluten-free bread with reduced starch digestibility	Higher total anthocyanin content of extracts
Products	Chinese jujube	Strawberry	Beef jerky	Beef jerky	Turkey breast meat	raw and cooked chicken breast meats	Fish granules	Abalone meat	Rice flour bread	Bilberry press cake
Drying methods	Combination of hot air drying and microwave drying	Combination of Vacuum and microwave drying	Infrared drying	Combined mid-infrared and hot air drying	Freeze drying	Convective air drying	Pulse-spouted vacuum-microwave drying	Cold air drying	Microwave drying	Infrared impingement drying

(Cao, Zhang, Mujumdar, Xiao, & Sun, 2007) and cattle jerky (Liu et al., 2013).

The combination of water-activity-lowering agents is widely utilized in the production of IMF, but the process is time consuming. For example, the dry-salting process of salted cod takes about 14 days (Schröder, 2010) and the drying process of dried salted ham and neck takes about 7 days (Kunová et al., 2015). It is also reported that during salting liquid oxidation can take place in marine catfish (Smith, Hole, & Hanson, 1990), salted sliver carp (Wang, Zhao, Yuan, and Jin, 2015). In order to solve these problems, new methods should be studied. Besides, water-activity-lowering agents alone may not be able to reduce a_w to the safety level for prevention of microbial growth. Subsequent methods, including pasteurization and packaging methods must be taken into consideration to achieve shelf stable IMF.

2.3. *Innovative osmotic dehydration techniques*

OD is a well-established partial dehydration process. Driven by a differential osmotic pressure between the medium and the products, a significant amount of free water removed from a high moisture food in an OD process (Ciurzyńska, Kowalska, Czajkowska, & Lenart, 2016). A typical mass transfer pattern of OD is shown in Fig. 1 in which the water flows to the outside of food material, and solutes in a hypertonic solution enter into the products. Since the cell membrane is not perfectly selective, the solutes present in cells (organic acids, sugars, minerals, fragrances, and colorants) can pass with water into the hypertonic solution (Nevena, Gordana, Ljubinko, Mariana, & Tatjana, 2008). OD becomes less effective when the differential osmotic pressure decreases with the process of dehydration thus leading to low efficiency of dewatering. It was found that factors, including temperature, osmotic time and the thickness of food product, can affect the water loss of OD. Efforts was undertaken by Cao, Zhang, Mujumdar, Du, and Sun (2006) to overcome the above challenge in dewatering of kiwifruit. The results showed that 60% sucrose concentration, 30–40°Cosmotic temperature, 150 min osmotic time, and 8 mm slice thickness were the optimal condition to obtain kiwifruit with high retention of vitamin C. Significant efforts have been reported in the literature that explored new and efficient technologies to overcome the above the shortcoming of long drying times. Among these new technologies, Vacuum Impregnation (VI) osmodehydro-freezing, MAOD and UAOD are most promising. These innovative technologies lead to extensive mass transfer and higher energy efficiency. The quality of the food products, obtained using these advanced technologies, is much better than that of food products produced by OD alone.

2.3.1. *Vacuum impregnation*

Combining VI with OD facilitate penetration of osmotic solutions into porous structures of animal and plant tissues in a controlled manner (Viana, Corrêa, & Justus, 2014). The displacement of osmotic solution and the gases contained in the pores of food structure is aided by additional deformation-relaxation phenomena during VI (Derossi, Iliceto, Pilli, & Severini, 2015). A VI operation is completed in two steps: (1) a relatively short vacuum period, e.g.,10 to 20 min is maintained when foods are immersed in an osmotic solution with a vacuum (p_1 ~ 50–100 mbar) applied to a container (Chwastek, 2014). This allows internal gases and liquids to migrate out of the capillary pores driven partially by the expansion of internal gases under vacuum; (2) a certain period, e.g., about 30 min, is maintained and the pressure of the container is restored to ambient level (Xie and Zhao, 2009). During the second step, osmotic solution is driven into the pores (Atarés, Chiralt, & González-Martínez, 2008; Gong et al., 2010). VI has been widely used in food industry as a pretreatment before drying, canning, freezing and frying. It has the ability to change the food formulation and produce novel food products. Several advantages have been reported to be associated with VI, including time-saving and better retention of nutrition and fresh sensory quality without exposing in oxygen and faster

Table 2
The usage and advantage of some novel water-activity-lowering agents.

Water-acivity-lowering agents	Products	Major results	References
Fiber colloid Xanthan gum (XG) Carboxymethyl cellulose (CMC)	Shrimps	Less impact on appearance, texture, and flavor than control samples	Torti (2016)
Composite phosphate, sorbitol and glycerol	Shrimps	Increase the quality and the shelf life	Cui, Xue, Xue, and Zhaojie (2013)
Plum concentrate or a blend of plum fiber and powder	Chicken marinade	Cause no change on sensory quality	Nathan (2012)
Fat and skim milk power	Smoked sausages	Improve the appearance and quality	Ahlawat (2012)
The mixture of potassium lactate and sodium diacetate	Frankfurter sausage	Result in a shelf-life extension with 75–125%	Stekelenburg (2003)
Sodium chloride-glycerol solution	Beef	Obtain diffusion coefficients	Favetto (2010)
Potato fiber	Tomato sauce	Decrease the aw	Diantom (2017)
Polysaccharides	Fresh and pickled mushrooms	Better resistance to oxidation	Khaskheli (2015)
Xylitol and oligofructose	Reduced-calorie sponge cake	Improve the appearance and quality	Nourmohammadi (2016)

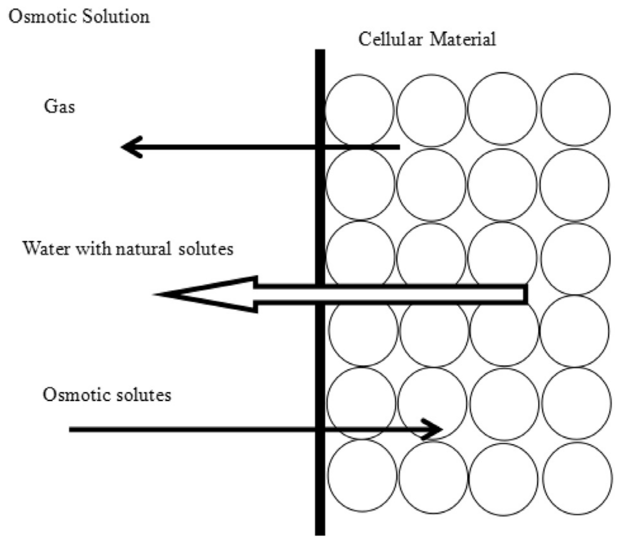

Fig. 1. Mass transfer pattern when a cellular material is immersed in osmotic solution.

permeation rate. For example, VI was applied to apples to prevent browning (Neri et al., 2016) and mangoes to facilitated water removal and sugar gain during the immerse process of 300 min by 20.6% and 31.3%, respectively (Lin, Luo, & Chen, 2016). Calcium-fortified pineapple snacks made by VI combined with air drying had porous and crunchy sensory quality and are easy to be stored (Lima et al., 2016). VI can largely reduce the time of the salting and thawing process for Spanish cured ham (Barat, Grau, Pagán-Moreno, & Fito, 2004). Chiralt et al. (2001) observed a notable reduction of salting time of VI in salting different food products such as meat (ham and tasajo), fish (salmon and cod) and cheese (manchego type cheese). Optimal processing conditions such as appropriate vacuum level, impregnation time in vacuum or at atmospheric pressure, concentration of extract, solid-liquid ratio and structure of food materials are conducive to the improvement of the quality and storage stability of VI products (Tylewicz, Romani, Widell, & Galindo, 2013). VI conditions should be carefully determined for specific products with desired quality attributes.

Pulsed vacuum impregnation (PVI) is another novel technology which involves the application of a short vacuum pulse at the beginning of an OD process (Derossi, Pilli, & Severini, 2010). PVI has been applied in the OD of sliced apples (Moreno et al., 2011; Paes, Stringari, & Laurindo, 2007) pineapples (Lombard, Oliveira, Fito, & Andrés, 2008), guavas (Panades et al., 2008), and mangoes (Giraldo, Talens, Fito, & Chiralt, 2003). For example, the water loss rate of raspberries is 3–4 times higher than the mass gain in the condition of 1.33 MPa for a period of 8 min (Bórquez, Canales, & Redon, 2010). The apple slices treated by PVI (0.013 MPa 10 min, followed by a relaxation period of 50 min at atmosphere) showed an increase of β-carotene(6mgβ-carotene/g dry solids)than OD alone for 10 min in which the content of β-carotene is 4.16mgβ-carotene/g dry solids (Santacruzvázquez, 2007). PVI has also been applied for blueberries to decrease the processing time, thereby, improving phenolic components and shelf life in contrast to traditional methods (Moreno et al., 2016). It is generally accepted that that VI and PVI are effective ways to reduce water, improve the quality of fresh foods, and use less processing time. However, technical challenges remains, such as how to control of mass transfer rate, how to reuse of VI solutions, and concern over microbial safety of the VI solutions. Incomplete immersion of samples in VI solutions might constitute an obstacle to the utilization of VI (Zhao & Xie, 2004). Further researches need to be carried out to overcome the above challenges for specific applications.

2.3.2. *Osmodehydro-freezing*

The conjunction process of OD and freezing, referred to osmodehydro-freezing in some literatures, is used to produce IMF with better textural properties and reduced structural collapse (Efimia K. Dermesonlouoglou, Pourgouri, & Taoukis, 2008). A unique advantage of this combination is that OD removes a part of water in fresh foods, thus reducing the available water for freezing and minimizing quality changes of food products upon thawing. Certain amount of water in foods remains unfrozen at temperatures below the freezing point of water which acts as the solvent for the solutes during the cold storage. Proteins can be made stable by ionic interaction which is affected by high electrolyte concentration.

Osmodehydro-freezing has been found to cause less unwanted changes and improve the quality of food products at low temperatures. In addition, osmodehydro-freezing is less cost and energy consumption than freezing alone (Ngamjit & Sanguansri, 2009).

Similiary, dehydro-freezing is another approach to producing frozen fruits with high nutrition value and desirable sensory qualities. Efimia K. Dermesonlouoglou, Giannakourou, and Taoukis (2016) reported that dehydro-freezing strawberries showed more color and vitamin C retention when compared to conventional strawberries. A good organoleptic quality and the strawberry tissue integrity were also obtained. Partial removal of water prior to freezing has been reported to enhance the final quality of cucumbers (Efimia K. Dermesonlouoglou et al., 2008). Zhao, Hu, Xiao, Yang, Liu, Gan, and Ni (2014a, b) reported that OD of mangoes prior to freezing reduced quality losses of the frozen foods. It particularly helps the retention of product color, texture, Vitamin C content, and reduces dip loss upon thawing, as compared to conventional frozen methods. Similarly, Dermesonlouoglou, Giannakourou, and Taoukis (2007) studied the effect of dehydro-freezing on tomato. The quality and stability of tomato were improved during storage. The retention of color, total lycopene and L-ascorbic acid in the dehydro-freezing samples was significantly increased, when compared to the untreated ones.

Freezing has been used before OD. Kowalska, Lenart, and Leszczyk

(2008) studied the effect of freezing before OD on the quality of pumpkin. The result showed that using freezing as a pretreatment for OD can increase the solid gain compared with the untreated samples. Similarly, observation has been made with pomegranate seeds by Bchir, Besbes, Attia, and Blecker (2012). After freezing the concentration of electrolyte is high which affects the interaction of ions, thus protecting the quality of food products.

2.3.3. Microwave assisted osmotic dehydration (MAOD)

MAOD is another novel combination treatment that can enhance moisture transfer in food products and reduce processing time. Researchers also combined microwave with OD to achieve superior quality foods. The application of microwave causes a rise of temperature in products and osmotic solution, thus increasing the mass transfer rate. The solid gain and water loss ratio are higher in MAOD than OD. Azarpazhooh and Ramaswamy (2012) studied mass transfer during microwave osmotic dehydration of apple cylinders. They compared microwave osmotic dehydration of apple with conventional OD, and found that the microwave osmotic dehydration was more effective in reducing the water. Botha, Oliveira, and Ahrné (2012) combined OD with microwave to optimize the quality of pineapple. With the combination of the two methods, the flexibility for process control and product quality were increased. Because water activity can be influenced by microwave power, drying time and the quality of food products can be controlled by changing the microwave power. Pereira, Marsaioli, and Ahrné (2007) studied the influence of microwave power, temperature and air viscosity on the final drying kinetics of bananas. It was found that with the increasing of microwave power the drying time was reduced and the quality was improved.

2.3.4. Ultrasound assisted osmotic dehydration (UAOD)

UAOD is a method that can improve the efficiency of OD (Mendonça, Corrêa, Junqueira, Pereira, & Vilela, 2016). Ultrasounds (US) are mechanical waves with frequencies ranging from 20 kHz to 100 MHz that can transmit through solids and liquid media via alternating volumetric expansion and compression. Microscopic channels may be created in fruit tissues by ultrasound. The escape of the gas trapped in the pores contributing to the entrance of osmotic solution into the empty pores. This increases in mass diffusion (Simal, Benedito, Sánchez, & Rosselló, 1998). The process take places at room temperature, so degradation of the product is minimized. This also leads to a fast and complete degassing, starting numerous reactions through creating radicals, increasing polymerization and depolymerization reactions as well as enhancing diffusion rates (Karizaki, Sahin, Sumnu, Mosavian, & Luca, 2013).

Nowacka, Tylewicz, Laghi, Rosa, and Witrowa-Rajchert (2014) reported the effect of ultrasound treatment on the water state in kiwifruit during OD. They found that treating kiwifruit products with US for > 10 min could create micro-channels and increase the average cross-section area of cells which significantly enhanced the mass exchange caused by OD. For example, ultrasound pretreatment of potato cubes in water increased the diffusivity during osmotic dehydration at solute concentration of 70% up to 130% (Goula, Kokolaki, & Daftsiou, 2017). Corrêa Justus, Oliveira, Alves, and Guilherme (2015) researched UAOD of tomato. They concluded that the mass transfer in OD could be improved with assistance of US. Dehghannya, Gorbani, and Ghanbarzadeh (2015) also used UAOD to treat mirabelle plum with a significant decrease (20%) in drying time which was beneficial in terms of less energy consumption and the maintenance of heat sensitive nutrients. Furthermore, Oliveira, Rodrigues, and Fernandes (2012) used ultrasound for the OD of Malay apple at low temperature. The ratio of solid gain and water loss was higher in samples treated by ultrasound as compared to untreated ones. The color, nutritional properties, flavor were also retained after process.

In summary, the above mentioned novel methods of OD greatly affect the kinetics of the process. These methods facilitate the removal of water from food materials thus shortening the time of OD, improving energy efficiency and enhancing product quality. In addition, functional and textural forming components can be introduced into the raw materials by altering the surface layer of the dehydrated food products. However, careful selection of relevant parameters is required for each product to achieve optimal results.

2.4. Electroosmotic dewatering

The motion induced by an applied electric field across a porous material, capillary tube, membrane, microchannel, or any other flow channel of liquid is called electroosmosis (Tanaka, Fujihara, Jami, & Iwata, 2014). Water removed by placing dewatering materials between two electrodes is referred to as electroosmotic dewatering. Although electroosmotic dewatering is not widely used in food industry, various investigations on electroosmotic dewatering were performed in food processing fields (Yoshida, Yoshikawa, & Kawasaki, 2013).

In electroosmotic dewatering, the voltage near the filter medium almost does not decrease and the effect of blocking on dewatering rate is very small. Compared to traditional dewatering methods electroosmotic dewatering is time saving (Tanaka et al., 2014). Electroosmotic dewatering is specifically effective for enhancing removal of water from solid–liquid mixtures containing colloidal materials and mixtures that are difficult to dewater mechanically. For example, tomato paste and vegetable sludge can be dewatered efficiently by this method. The water of tomato paste can be reduced by using electroosmotic dewatering. They found an increase in the dewatering rate can be achieved by decreasing the wave frequency resulted in or increasing the initial bed height. (Banat, 2005). Chen, Mujumdar, and Ragbaran (1996) did laboratory experiments on dewatering of vegetables sludge. They used three dewatering methods for vegetables sludge, including electroosmotic dewatering, pressure dewatering, and the combination of both. Results showed the combined dewatering methods was more effective than electroosmotic dewatering and pressure dewatering. The experiments suggest feasible industrial application of electroosmotic dewatering on the water removal from food products. The apparatus of electroosmotic dewatering is shown in Fig. 2.

Many factors can affect the effectiveness of a electroosmotic dewatering process, including the production and transport of hydrogen and hydroxyl ion in the food products, the changes of water morphology of food and the bubbles (Lee, 2009). However there are limited knowledge about electroosmotic dewatering nowadays, much more research works needed to be collected from solid–liquid systems, so that they can be used to access and improve the electroosmotic dewatering devices.

3. Novel technologies for preserving IMF

3.1. Methods for sterilizing/inhibit microorganism in IMF

Thermal processing is the most effective means to in activate pathogenic and spoilage micro-organisms. Thermal processing can be divided into pasteurization (≤100 °C) and commercial sterilization (> 100 °C). Thermal processing has been extensively used in the food industry for production of ready-to-eat high moisture products, but commonly used for IMF. With increasing food safety concerns associated with low moisture food and IMF, thermal pasteurization can be an effective option to ensure food safety of pre-packaged IMF. Non-thermal methods for microbial reduction of food products have recently received considerable interest. These technologies are carried out at around the ambient temperature and thus, eliminate the adverse effects on food quality associated with the traditional thermal methods. Some representative publications that concerning the usage of non-thermal decontamination technologies are listed in Table 3. Among these non-thermal methods, CP, HPP and coating technologies are considered to be promising and novel technologies.

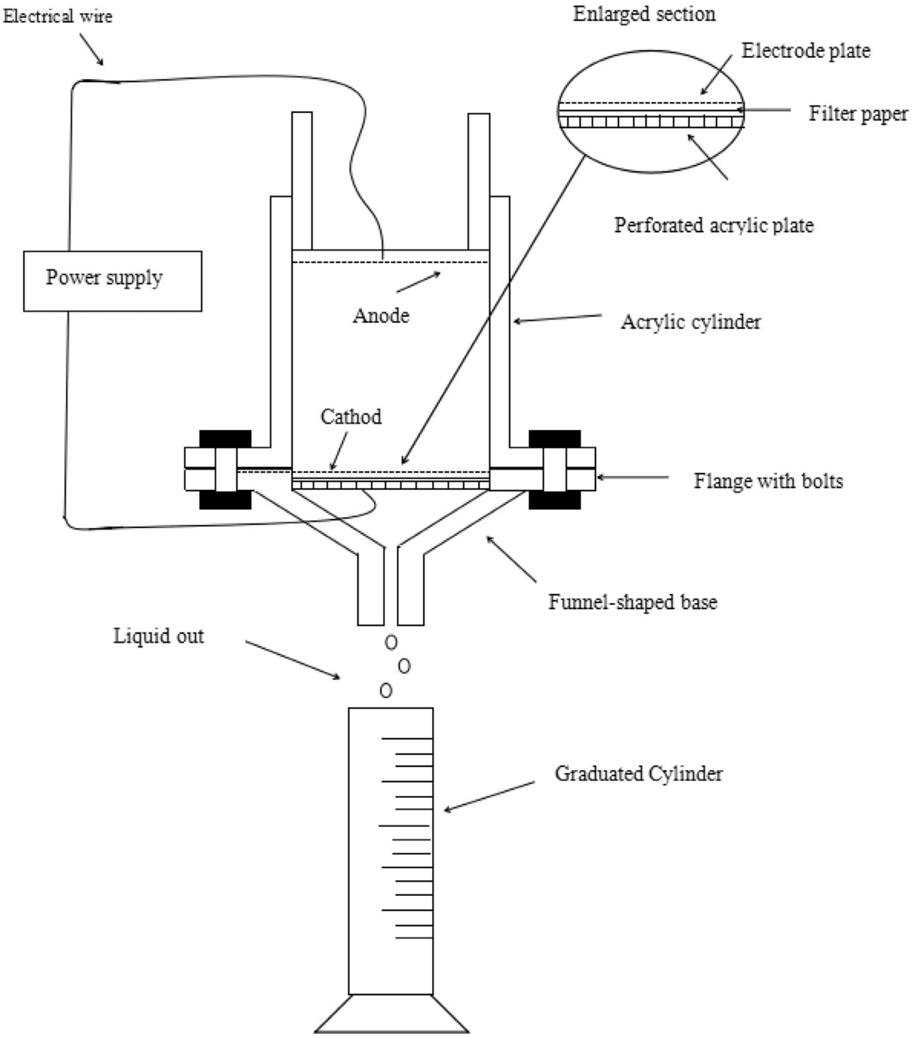

Fig. 2. Electroosmosis dewatering apparatus.

3.1.1. *Thermal pasteurization*

Thermal pasteurization has been studied for several IMF such as Kiwi jam (a_w 0.78) (Lespinard, Bambicha, & Mascheroni, 2012), gluten-free fresh filled pasta (water content 48%) (Sanguinetti et al., 2016) and meat products (water content 54%) (Selby et al., 2006). Pasteurization (65 °C,30 min) can be used in honey (a_w 0.68) to reduce the pH value and the pasteurized sample was accepted by consumers (Ribeiro, Villas-Bôas, Spinosa, & Prudencio, 2018). Fernando, Arturo Rivera, Guiomar Denisse, and Rosa María (2014) studied the effect of thermal pasteurization(65 °C,15 min) on the sensory quality and the growth of endogenous microorganism of packed sliced cooked meat product (a_w 0.97). They found that the growth rate of microorganism was lower and the sensory quality is higher than the control. Thermal pasteurization (60 °C, 120 s and 68 °C,12 s) was also applied to emulsion vacuum packaged sausages to prevent spoilage and prolong the shelf life in refrigerated storage (Abhari, Jafarpour, & Shekarforoush, 2018). The

Table 3
The usage of non-thermal decontamination technologies.

Applied technology	Products	Achieved effects	References
Aqueous ozone treatment	Semi-dried buckwheat noodles	The shelf life was extended for 9 days with textural and sensorial characteristics unchanged.	maintaining higher vitamin C and less shrinkage of product. Maintaining higher vitamin C and less shrinkage of product. Bai (2017)
Plasma treatment	Semi-dried squid	The shelf life of the samples was extended with the sensory and other characteristics unchanged.	Choi (2017)
	Bacon		Kim (2011)
	Sliced cheese		Song (2009)
	Ham		Yun (2010)
High hydrostatic pressure	Semi-dried squid	The shelf life of the samples was extended.	Gou (2012)
Gamma irradiation	Traditional Korean half-dried seafood products	Gamma irradiation (7 kGy) was effective without affect color and sensory characteristics.	Kang (2015)
Coating	Grass carp	Coating using 1 and 2% chitosan, the shelf-life of grass carp can be extended by 3 and 6–7 days respectively.	Yu (2016).

data showed for both pasteurized groups, the shelf life was extended to > 3 months without affecting the sensory quality.

Recent studies have revealed that thermal resistance of bacterial pathogens, e.g., *Salmonella* and *Listeria monocytogenes*, increases sharply with reduction in water activity of food matrices measured at treatment temperatures (Liu et al., 2018; Li, Kou, Zhang, et al., 2018; Taylor et al., 2018). Thus, much higher processing temperature or longer time are needed for thermal pasteurization of IMF as compared to the high moisture counterparts, even for the same target bacterial pathogens. Such processes may cause thermal degradation of heat sensitive quality attributes. Thermal technologies for preserving IMF should be carefully selected to achieve a balance between shelf life and the food quality. After meeting microbial safety requirements serious consideration should be given to the quality changes of food products during processing and storage. Optimization of pasteurization condition should be carried out by considering the thermal kinetics of the target pathogens, thermal inactivation of quality-related enzymes, and related quality parameters (Peng et al., 2017). Storage tests should also be carried out at normal distribution and storage conditions to ensure microbial safety and acceptance of food products within their maximum shelf life.

3.1.2. Plasma treatment

Plasma treatment (PT) is a relatively new decontamination technology compared to traditional thermal decontamination technologies in the food industry. It can efficiently inactivates microorganisms, including biofilms, bacterial spores, fungi and bacteria (Segat, Misra, Cullen, & Innocente, 2016). Plasma is an ionized gas that consists of charged particles, electric fields, UV photons, and reactive species (Ma et al., 2015), all of which are considered to be effective to inactive microorganisms and ensure the safety of food products. Three basic mechanisms are induced by PT and contribute to cell death: (1) etching of cell surfaces induced by reactive species formed during plasma generation, (2) volatilization of compounds and intrinsic photodesorption of ultraviolet (UV) photons, and direct damage to gene (Laroussi, 2010). PT has been applied to the sterilization of medicine instruments and the treatment of material surfaces. Plasma can be divided into two categories, namely low-temperature plasma (LTP) and thermal plasma (TP). Different terms have been used for Low-temperature plasma (LTP) by various researchers, such as atmospheric cold plasma (ACP), non-thermal plasma (NTP), atmospheric pressure plasma (APP) or simply cold plasma (CP) (Stoica, Alexe, & Mihalcea, 2014). Formerly, the PT was carried out in vacuum environment, but now an atmospheric plasma system has been designed to reduce the cost, increase the treatment speed and apply in industry.

LTP has been applied to various food products to inactive microorganism and achieve longer shelf life. For example, Kim et al. (2011) applied APP to the bacon, and found the safety of the treated bacon was improved without significant color changes. APP was also applied to IMF, such as sliced cheese (Song et al., 2009) and ham (Yun et al., 2010). In addition, LTP has also been widely used in the decontamination of seafood products to maintain a balance between sensory properties and food safety. Puligundla, Choi, and Mok (2017) used CP to improve the hygienic quality of semi-dried pacific saury. The physicochemical and sensory properties of the final products were virtually unchanged by the treatment except for thiobarbituric acid reactive substances and color. The sanitary quality of semi-dried squid was also improved by CP. They found that semi-dried squid (water content 54.8%) with better sensory properties (visual appearance, color and flavor) compared to the control ones can be achieved by CP (Choi, Puligundla, & Mok, 2017).

PT has become a newcomer to the food industry. It processes various advantages such as high efficiency of microbial inactivation, little damage to food products, absence of water, solvents and residues. It is also an environment-friendly decontamination technology of high efficiency (Misra, Tiwari, Raghavarao, & Cullen, 2011). On the other hand, incomplete sterilization caused by the limited extent of penetration of plasma species have hindered the applicability of PT. Nowadays, thermal decontamination technologies have served the food industry very well, and the application of PT has been limited to laboratory tests. It has also been reported that the sensory acceptance and the production of undesirable flavors have not been extensively researched (Misra et al., 2011).

3.1.3. High pressure processing (HPP)

High pressure processing (HPP) is an innovative non thermal method for the treatment of food products, especially juices and muscle-containing products such as fish and meats. The mechanism is based on the sublethal damage of microbial cells at high pressure combined with low temperature and hold time (Sevenich, Rauh, & Knorr, 2016). The thermal load of HPP is lower than other thermal treatments, HPP has several benefits over other methods. The quality and nutritional quality of food products are not greatly influenced and the shelf life of food products can be prolonged due to the reduction of microorganism.

HPP has been applied to the sliced RET “lacón” by Olmo, Calzada, and Nuñez (2014). The authors found that gram-negative bacteria can be controlled and the sensory quality stayed little changed during refrigerated storage (4 °C, 120 days). The process parameters included 500 MPa pressure, 5 min processing time, and process temperature between 9 °C and 16 °C. HPP has also been used in the preservation of ready-to-heat vegetable meals by Masegosa, Delgado-Adámez, Contador, Sánchez-Íñiguez, and Ramírez (2014). They found that HPP at 600 MPa for 5 min can extend the shelf life of RET vegetables. For the process, the initial water temperature in the high pressure vessel during HPP was 10 °C. The results are consistent with other studies (Stratakos, Linton, Patterson, & Koidis, 2015).

HPP technology is expensive, it has been used in developed countries for production of meats and juices that require cold storage. The effect of HPP on microbial inactivation in IMP is not well documented and requires further research. In addition, more research is needed on integrity of food packages and sensory properties of specific products (Stratakos, Linton, et al., 2015).

3.2. Packaging methods

3.2.1. Edible coating

After dewatering by adding water-activity-lowering agents, osmotic dehydration, drying and other dehydration methods, the quality and stability of IMF may be impaired by environment and biochemical changes and microbial growth. Heavy losses may occur in the distribution chain (Buzby, Farahwells, & Hyman, 2014). In order to enhance the quality and shelf life of IMF, numerous attempts have been made by researchers. Edible coating is one of the most promising options which can prevent the food products from mechanical and microbial damage. It may also reduce loses of volatiles and provide IMF an esthetic appearance. The fact that edible coating can be safely consumed along with food products has motivated increasing interest among consumers. Edible coating is a thin layer of edible materials applied to the surface of food materials in a liquid form on the food to be coated after dehydration. It acts as a barrier to moisture loss, and microbial damage of food products, thus extending the shelf life of food products (Al-Abdullah, Angor, Al-Ismai, & Ajo, 2011). Lipids, hydrocolloids and composites are commonly used as edible coating materials in the food industry. For example, coating using 1 and 2% chitosan, the shelf life of grass carp can be extended by 3 and 6–7 days respectively and the bacterial growth can be effectively inhibited without influencing the sensory and nutritional qualities of it (Yu, Li, Xu, Jiang, & Xia, 2016). Similarly, Wang, Cao, sun, and Qin (2012) used a composite antimicrobial coating made by carboxymethylcellulose (CMC) and gelatin to preserve bacon. A slow decay rate and prolonged storage period can be made. Sergio et al. (2017) used chitosan coating in place of the polyethylene packaging to produce shelf stable semi-dried meat. The samples coated by chitosan showed lower thiobarbituric acid-reactive substance than the control ones in the storage (up to 4 weeks) at room temperature.

Recently, novel coating materials have shown their potential for quality protection and bacteria inhibition. Silver nanoparticles (AgNPs) was used as an antimicrobial coating to prevent the growth of lactic acid bacteria in chicken sausages to extend the shelf life of them (Marchiore et al., 2017). The antilisterial efficacy of novel coating solutions made with organic acids, lauric arginate ester, and chitosan can be used for color protection and controlling listeria contamination (Wang, Zhao, Yuan, & Jin, 2015). The combined application of chitosan and clove oil was capable of effectively inhibiting microbial growth, retarding lipid oxidation and extending the shelf life of cooked pork during refrigerated storage (Lekjing, 2016). The combination of κ-carrageenan, alginate and gellan was used by researchers to preserve chesses. It was found that the coated cheese had better textural and sensorial properties compared to non-coated ones without influencing the taste of the samples (Kampf, & Nussinovitch, 2000). Coating is widely used for lowering lipid oxidative changes, sensory properties preservation and microbiological control (Alemán et al., 2016). Novel coating materials are harmless and the residues in the food are less, which cause no damage to our bodies.

In conclusion, edible coating has demonstrated several advantages, such as being nontoxic, non-polluting, edibility and biodegradability, over conventional plastic packages. The shelf life of IMF can be extended by inhibiting microbial growth, reducing lipid oxidation and preventing the contact of food materials with the outer environment. But most of the studies on edible coating for food applications have been limited to laboratory tests. Further research is needed for scaling up to commercial applications. It is of vital significance to understand the interactions between the active ingredients and food materials before applying new edible coating materials. There exists a knowledge gap that needs to be filled on the effect of active ingredients on the functional, mechanical and sensory qualities of edible coatings.

3.2.2. Modified atmosphere packaging (MAP) and active packaging (AP)

Packaging is needed to maintain the integrity and quality of IMF during distribution and in storage. Additional benefits can be added by carefully selecting appropriate packaging technologies. MAP has attracted much attention recent years as a valid method to inhibit microbial growth and enzymatic spoilage. It has been widely used as an effective method to extend shelf-life of fresh produce, by limiting the exchange of respiratory gases in packages made of semi permeable plastic films (Chitravathi, Chauhan, & Raju, 2015). Oxygen (O_2), carbon dioxide (CO_2) and nitrogen (N_2) are most commonly used gases in MAP. CO_2 is an important component in the gas mixture because of its antibacterial activity (Sun et al., 2017). N_2 is an inert gas which does not have any antibacterial ability and is usually served as a filler gas in the gas mixture. MAP relies on the modification of the atmosphere inside the package to obtain a balance between gas transmission through package and gas consumption via respiratory process. AP is another effective packaging method for the preservation of IMF by adding a chemical compound to the packaging materials. The most commonly used chemical is O_2 absorber which can change the headspace gas composition and absorb the O_2 to < 0.01% within 1–4 days at room temperature.

MAP has been used in the package of part-baked Sangak bread (Khoshakhlagh, Hamdami, Shahedi, & Le-Bail, 2014), smoked catfish (Goktepe & Moody, 2010), and intermediate-moisture egg-based sliced wheat flour bread (Rodríguez, Medina, & Jordano, 2000) to prolong the shelf life without affecting the sensory quality of the product. MAP has been widely used to preserve and extend the shelf life of food products in both developing and developed countries for its low investment cost and simplicity. Egg-based desserts (a_w 0.87) called “fios de ovos” with intermediate moisture was packed using MAP to extend the shelf life. The shelf life of the desserts was increased by 2 fold under MAP (60% CO_2, 40% N_2) and 5 fold under AP (Suppakul, Thanathammathorn, Samerasut, & Khankaew, 2016). The shelf life of ready-to-cook fresh skewer (moisture content ranging from 65% to 75%) packaged by MAP (50%O_2, 30%CO_2, 20%N_2) can be extended by about 83% compared to the samples packaged in air (Gammariello, Incoronato, Conte, & Nobile, 2015). The combination of nitrogen (N_2) and CO_2 were also used in research to preserve fresh cheese and semi-dried green asparagus. Brown, Forauer, and D'Amico (2018) compared the effects of different package methods (air, vacuum, and combinations of N_2 and CO_2) on the shelf life of fresh cheese. Results showed that MAP with the combination of N_2 (30%) and CO_2 (70%) can prolong the shelf life of fresh cheese during cold storage. Sergio et al. (2017) found that semi-dried green asparagus cooked by microwave drying and stored in cold condition packaged by MAP (30%CO_2, 70%N_2) can obtain the longest storage period for 30 days.

However, many factors influence it effectiveness, including types of food materials, storage conditions and the characteristics of packaging materials. So packaging materials, storage conditions should be carefully chosen for different kinds of food materials (Brown et al., 2018).

AP has also been applied to various IMF such as pre-baked buns (Franke, Wijma, & Bouma, 2002) organic RTE iceberg lettuce (Wieczyńska & Cavoski, 2018) and bakery products (Guynot, Sanchis, Ramos, & Marín, 2010). AP is reported to extend the shelf-life of desserts (a_w 0.87) 3 fold longer than MAP (60% CO_2, 40% N_2) (Suppakul et al., 2016). Stratakos, Delgado-Pando, Linton, Patterson, and Koidis (2015) reported that that AP was able to preserve the color of chicken breast during the storage period (4 °C, 60 days). AP also displayed a potential in the package of RTE poultry meat. It was found that AP with ZnO nanoparticles can inhibit the number of inoculated target bacteria from 7 log to zero within 10 days during the process of incubation at 8 ± 1°Cs (Akbar & Anal, 2014). However, the technology is limited in Europe, because of legislative restrictions. The application of AP is found more often in the chain of product distribution than the retail markets.

It can be concluded from the literature that AP is an effective package method to reduce food safety risk and maintain the food quality. Various chemical materials can be used in AP to ensure food safety during storage. Although AP brings many benefits, it is possible that the components in the package will migrate into the food products during long time of storage thus endangering people's health. The ability of active materials to preserve their original mechanical and barrier properties after adding the active substances is a major technical challenge for AP. So new AP materials should be developed to solve the current issue.

3.3. Hurdle technology (HT)

Traditional preservation methods often use a single physical or chemical hurdle applied at a relatively high level that contributes to noticeable changes to sensory qualities of the preserved food. The hurdle technology combines the low levels of two or more preservation hurdles thus causing little damage to the quality of food products (Aguilera & Chirife, 1994). The hurdle technology was used by various researchers for the preservation of various food products.Jafari and Emam-Djomeh (2007) used hurdles to reduce the nitrite content of hot dogs without sacrificing the sensory quality and safety of the products. In their process, humectants were used to lower a_w to 0.95, the PH value of hog dogs was adjusted to 5.4 using glocono-delta-lacton. Moreover, the internal temperature was increased to 75 °C by keeping the samples at 80 ± 1 °C for an hour and then cooled to 5–6 °C within 40-45 min. Finally, the hot dog was kept at chilled temperature during storage period. The nitrite content of the hurdle treated samples (50 ppm) was sharply decreased compared to the nitrite content of control ones (120 ppm) without affecting the overall acceptability and sensory attributes. Soliva-Fortuny, Elez-MartíNez, Sebastián-Calderó, and MartíN-Belloso (2004) studied the effects of hurdle methods on the preservation of avocado puree during four months storage period at 4 °C or 22 °C. The addition of sorbic acid significantly affected the microbiological stability and 300 mg/kg sorbic acid was sufficient to inhibit the growth of microorganisms. The samples can also be preserved without adding sorbic acid, by combining the application of vacuum package and storage at 4 °C. Maltose can extend the shelf life slightly by lowering a_w of samples. However, the usage of sugar alone to achieve the required level of preservation is likely to affect the sensory characteristics. Hurdle technology was also used in the preservation of intermediate moisture (IM) spiced mutton and spiced chicken products (a_w 0.8) (Kanatt, Chawla, Chander, & Bongirwar, 2002). In this study, the a_w of samples was reduced to 0.80 by hot air drying or grilling. Then vacuum package and eradiated at 0–10 kGy. The shelf life of the samples increased with the increase of irradiation dose. The shelf life of samples subjected to irradiation at 10 kGy was extended by about 7 months without sensory changes compared to the samples without irradiation processing. Hurdle technology was also used by Kanatt, Chawla, Chander, and Sharma (2006) for the development of RTE shrimps (a_w 0.85). The hurdles applied to the samples included water activity reduction (0.85 ± 0.02) and γ-irradiation (2.5 kGy). But a visible mold growth was observed at room temperature within 15 days of storage, no significant changes of textural and sensory qualities were observed in the radiation samples.

Hurdle technology has been used in the preservation of various food products, including fruits, vegetables and meat products. It is a gentle but effective method for food preservation. The hurdles can be used at optimum level to get a maximum lethality against microorganisms but a minimum damage to food products through combining two or more hurdles together.

4. Concluding remarks

This paper reviewed recent developments in IMF production and preservation methods The novel preservation technologies including physical and chemical approaches, such as innovative drying methods, novel osmotic dehydration, adding water-activity-lowering agents, electroosmotic dewatering, edible coating, PT, HPP, MAP, AP and HD. Each technology has advantages and disadvantages when used for IMF.

Water content and a_w have a close relationship with the quality (flavor, color, taste and so on) of IMF. Traditional methods have some limitations such as time consuming and lower efficiency. The quality of the final products is poor. In order to produce high quality IMF as well as achieve high energy and drying efficiency, more attention must be paid to innovative technologies and novel combined dewatering methods. Combined technologies play important roles in reducing water of IMF as they can make the best use of each drying method and overcome the disadvantages of drying methods alone. Nowadays, the consumer's demand for IMF are expanding, to which combined drying methods for energy saving and products with high quality have been applied.

As for the preservation of IMF, novel microbial reduction, packing methods and the combination of multiple hurdles should be considered. Non-thermal methods have attracted considerable attention recently for maintaining a balance between quality and shelf life of IMF. But some technologies are uncommon and the cost are high, and the inactivation mechanisms for pathogens are unclear. More systematic research is required to fully utilize the potential of the latest novel technologies for preserving IMF.

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References

Abhari, K., Jafarpour, D., & Shekarforoush, S. S. (2018). Effects of in-package pasteurization on prevening spoilage in emulsion vacuum packaged sausages during refrigerated storage. *Foods & Raw Materials, 6*(1), 40–46.

Adiletta, G., Senadeera, W., Liguori, L., Crescitelli, A., Albanese, D., & Russo, P. (2015). The influence of abrasive pretreatment on hot air drying of grape. *Food and Nutrition Sciences, 6*(3), 355–364.

Aguilera, J. M., & Chirife, J. (1994). Combined methods for the preservation of foods in Latin America and the CYTED-D project. *Journal of Food Engineering, 22*(1–4), 433–444.

Ahlawat, S. S. (2012). Development of low fat emulsion based smoked sausages using different humectants. *Journal of Dairying Foods & Home Sciences, 31*, 306–310.

Akbar, A., & Anal, A. K. (2014). Zinc oxide nanoparticles loaded active packaging, a challenge study against Salmonella typhimurium and Staphylococcus aureus in ready-to-eat poultry meat. *Food Control, 38*(4), 88–95.

Aktaş, M., Şevik, S., & Aktekeli, B. (2016). Development of heat pump and infrared-convective dryer and performance analysis for stale bread drying. *Energy Conversion and Management, 113*, 82–94.

Al-Abdullah, B. M., Angor, M. M., Al-Ismai, K. M., & Ajo, R. Y. (2011). Reducing fat uptake during deep-frying of minced chicken meat-balls by coating them with some hydrocolloids materials. *Italian Journal of Food Science, 23*, 331–337.

Alemán, A., González, F., Arancibia, M. Y., López-Caballero, M. E., Montero, P., & Gómez-Guillén, M. C. (2016). Comparative study between film and coating packaging based on shrimp concentrate obtained from marine industrial waste for fish sausage preservation. *Food Control, 70*, 325–332.

Annie, D., Chandramouli, V., Anthonysamy, S., Ghosh, C., & Divakar, R. (2017). Freeze drying vs microwave drying–methods for synthesis of sinteractive thoria powders. *Journal of Nuclear Materials, 484*, 51–58.

Askari, G. R., Emam-Djomeh, Z., & Mousavi, S. M. (2013). Heat and mass transfer in apple cubes in a microwave-assisted fluidized bed drier. *Food and Bioproducts Processing, 91*(3), 207–215.

Atarés, L., Chiralt, A., & González-Martínez, C. (2008). Effect of solute on osmotic dehydration and rehydration of vacuum impregnated apple cylinders (cv. Granny Smith). *Journal of Food Engineering, 89*(1), 49–56.

Azarpazhooh, E., & Ramaswamy, H. S. (2012). Modeling and optimization of microwave osmotic dehydration of apple cylinders under continuous-flow spray mode processing conditions. *Food and Bioprocess Technology, 5*(5), 1486–1501.

Banat, F. (2005). Electroosmotic dewatering of tomato paste suspension under ac electric field. *Drying Technology, 23*(7), 1465–1475.

Barat, J. M., Grau, R., Pagán-Moreno, M. J., & Fito, P. (2004). Replacement of pile salting by simultaneous brine thawing-salting in Spanish cured ham manufacturing. *Meat Science, 66*(3), 603–608.

Bchir, B., Besbes, S., Attia, H., & Blecker, C. (2012). Osmotic dehydration of pomegranate seeds (Punica Granatuml.): Effect of freezing pre-treatment. *Journal of Food Process Engineering, 35*(3), 335–354.

Beuchat, L. R., Komitopoulou, E., Beckers, H., Betts, R. P., Bourdichon, F., Fanning, S., & Ter Kuile, B. H. (2013). Low–water activity foods: Increased concern as vehicles of foodborne pathogens. *Journal of Food Protection, 76*(1), 150–172.

Bórquez, R. M., Canales, E. R., & Redon, J. P. (2010). Osmotic dehydration of raspberries with vacuum pretreatment followed by microwave-vacuum drying. *Journal of Food Engineering, 99*(2), 121–127.

Botha, G. E., Oliveira, J. C., & Ahrné, L. (2012). Quality optimisation of combined osmotic dehydration and microwave assisted air drying of pineapple using constant power emission. *Food and Bioproducts Processing, 90*(C2), 171–179.

Brown, S. R. B., Forauer, E. C., & D'Amico, D. J. (2018). Effect of modified atmosphere packaging on the growth of spoilage microorganisms and Listeria monocytogenes on fresh cheese. *Journal of Dairy Science, 101*(9), 7768–7779.

Bruijn, J., Rivas, F., Rodriguez, Y., Loyola, C., Flores, A., Melin, P., & Borquez, R. (2015). Effect of vacuum microwave drying on the quality and storage stability of strawberries. *Journal of Food Processing & Preservation, 40*(5), 1104–1115.

Buzby, J. C., Farahwells, H., & Hyman, J. (2014). The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States. *Economic Information Bulletin*. https://doi.org/10.2139/ssrn.2501659.

Cao, H., Zhang, M., Mujumdar, A. S., Du, W.-h., & Sun, J.-c. (2006). Optimization of osmotic dehydration of kiwifruit. *Drying Technology, 24*(1), 89–94.

Cao, H., Zhang, M., Mujumdar, A. S., Xiao, G.-n., & Sun, J.-c. (2007). Study on reduction of water activity and storage stability for dehydrated brassica parachinensis with intermediate moisture. *Drying Technology, 25*(4), 669–674.

Carla, S., Mariarosaria, C., Antonio, D., Antonio, B., & Roma, G. (2008). Use of humectants for the stabilization of pesto sauce. *International Journal of Food Science and Technology, 43*(6), 1041–1046.

Carla, S., Rosaria, C. M., Antonio, D., Antonio, B., & Roma, G. (2010). Use of humectants for the stabilization of pesto sauce. *International Journal of Food Science and Technology, 43*(6), 1041–1046.

Çelen, S., Aktaş, T., Karabeyoğlu, S. S., & Akyildiz, A. (2016). Drying behavior of prina (crude olive cake) using different types of dryers. *Drying Technology, 34*(7), 843–853.

Chaijan, M., Panpipat, W., & Nisoa, M. (2016). Chemical deterioration and discoloration of semi-dried tilapia processed by sun drying and microwave drying. *Drying Technology, 35*(5), 642–649.

Chen, H., Mujumdar, A. S., & Ragbaran, G. S. V. (1996). Laboratory experiments on electroosmotic dewatering of vegetable sludge and mine tailings. *Drying Technology, 14*(10), 2435–2445.

Chiralt, A., Fito, P., Barat, J. M., Andres, A., Gonzalez-Martnez, C., Escriche, I., & Camacho, M. M. (2001). Use of vacuum impregnation in food salting process. *Journal of Food Engineering, 49*(2), 141–151.

Chitravathi, K., Chauhan, O. P., & Raju, P. S. (2015). Influence of modified atmosphere packaging on shelf-life of green chillies (*Capsicum annuum* L.). *Food Packaging & Shelf Life, 4*, 1–9.

Choi, S., Puligundla, P., & Mok, C. (2017). Impact of corona discharge plasma treatment on microbial load and physicochemical and sensory characteristics of semi-dried squid (Todarodes pacificus). *Food Science and Biotechnology, 26*(4), 1–8.

Chwastek, A. (2014). Methods to increase the rate of mass transfer during osmotic dehydration of foods. *Acta Scientiarum Polonorum. Technologia Alimentaria, 13*(4), 341–350.

Ciurzyńska, A., Kowalska, H., Czajkowska, K., & Lenart, A. (2016). Osmotic dehydration in production of sustainable and healthy food. *Trends in Food Science and Technology, 50*, 186–192.

Corrêa Justus, J. L. G., Oliveira, A. D., Alves, L. F., & Guilherme, E. (2015). Osmotic dehydration of tomato assisted by ultrasound: Evaluation of the liquid media on mass transfer and product quality. *International Journal of Food Engineering, 11*(4), 505–516.

Cui, H., Xue, C., Xue, Y., Wei, S., Li, Z., & Cong, H. (2013). Development of shelf-stable, ready-to-eat (RTE) shrimps (Litopenaeus vannamei) using water activity lowering agent by response surface methodology. *Journal of Food Science and Technology, 50*(6), 1137–1143.

Cui, H., Xue, C., Xue, Y., & Zhaojie (2013). Development of shelf-stable, ready-to-eat (RTE) shrimps (Litopenaeus vannamei) using water activity lowering agent by response surface methodology. *Journal of Food Science and Technology, 50*(6), 1137–1143.

Dagnas, S., Gougouli, M., Onno, B., Koutsoumanis, K. P., & Membré, J. M. (2017). Quantifying the effect of water activity and storage temperature on single spore lag times of three moulds isolated from spoiled bakery products. *International Journal of Food Microbiology, 240*, 75.

Darvishi, H., Azadbakht, M., Rezaeiasl, A., & Farhang, A. (2013). Drying characteristics of sardine fish dried with microwave heating. *Journal of the Saudi Society of Agricultural Sciences, 12*(2), 121–127.

Dehghannya, J., Gorbani, R., & Ghanbarzadeh, B. (2015). Effect of ultrasound-assisted osmotic dehydration pretreatment on drying kinetics and effective moisture diffusivity of mirabelle plum. *Journal of Food Processing & Preservation, 39*(6), 2710–2717.

Dermesonlouoglou, E. K., Giannakourou, M., & Taoukis, P. S. (2016). Kinetic study of the effect of the osmotic dehydration pre-treatment with alternative osmotic solutes to the shelf life of frozen strawberry. *Food and Bioproducts Processing, 99*, 212–221.

Dermesonlouoglou, E. K., Giannakourou, M. C., & Taoukis, P. (2007). Stability of dehydrofrozen tomatoes pretreated with alternative osmotic solutes. *Journal of Food Engineering, 78*(1), 272–280.

Dermesonlouoglou, E. K., Pourgouri, S., & Taoukis, P. S. (2008). Kinetic study of the effect of the osmotic dehydration pre-treatment to the shelf life of frozen cucumber. *Innovative Food Science & Emerging Technologies, 9*(4), 542–549.

Derossi, A., Iliceto, A., Pilli, T. D., & Severini, C. (2015). Application of vacuum impregnation with anti-freezing proteins to improve the quality of truffles. *Journal of Food Science and Technology, 52*(11), 7200–7208.

Derossi, A., Pilli, T. D., & Severini, C. (2010). Reduction in the pH of vegetables by vacuum impregnation: A study on pepper. *Journal of Food Engineering, 99*(1), 9–15.

Fang, S., Wang, Z., Hu, X., & Ashimk, D. (2009). Hot-air drying of whole fruit Chinese jujube (Zizyphus jujuba Miller): Physicochemical properties of dried products. *International Journal of Food Science and Technology, 44*(44), 1415–1421.

Fang, S., Wang, Z., Xiaosong, H. U., Chen, F., Zhao, G., Liao, X., & Zhang, Y. (2011b). Energy requirement and quality aspects of Chinese Jujube (Zizyphus Jujuba Miller) in hot air drying followed by microwave drying. *Journal of Food Process Engineering, 34*(2), 491–510.

Fernando, P. R., Arturo Rivera, Z., Guiomar Denisse, P. I., & Rosa María, G. G. (2014). Study of the effect of post-packaging pasteurization and argon modified atmosphere packaging on the sensory quality and growth of endogenous microflora of a sliced cooked meat product. *Food science and technology international = Ciencia y tecnología de los alimentos internacional, 20*(1), 3.

Finn, S., Rogers, L., Händler, K., Mcclure, P., Amézquita, A., Hinton, J. C., & Fanning, S. (2015). Exposure of Salmonella enterica Serovar typhimurium to three humectants used in the food industry induces different osmoadaptation systems. *Applied and Environmental Microbiology, 81*(19), 6800.

Franke, I., Wijma, E., & Bouma, K. (2002). Shelf life extension of pre-baked buns by an ACTIVE PACKAGING ethanol emitter. *Food Additives & Contaminants, 19*(3), 314–322.

Gammariello, D., Incoronato, A. L., Conte, A., & Nobile, M. A. D. (2015). Use of sodium lactate and modified atmosphere packaging for extending the shelf life of ready-to-cook fresh meal. *Packaging Technology and Science, 28*(2), 101–112.

Giraldo, G., Talens, P., Fito, P., & Chiralt, A. (2003). Influence of sucrose solution concentration on kinetics and yield during osmotic dehydration of mango. *Journal of Food Engineering, 58*(1), 33–43.

Goktepe, I., & Moody, M. W. (2010). Effect of modified atmosphere packaging on the quality of smoked catfish. *Journal of Muscle Foods, 9*(4), 375–389.

Gong, Z. Q., Gao, L. Y., An, J. S., Min, Z., Mujumdar, A. S., & Sun, J. C. (2010). Effects of predrying and vacuum impregnation with nano-calcium carbonate solution on strawberries, carrots, corn, and blueberries. *Drying Technology, 28*(1), 36–41.

Goula, A. M., Kokolaki, M., & Daftsiou, E. (2017). Use of ultrasound for osmotic dehydration. The case of potatoes. [Article]. *Food & Bioproducts Processing: Transactions of the Institution of Chemical Engineers Part C, 105*, 157–170.

Guo, D. J., Xiong, S. B., Song, Z., & Liu, R. (2014). Effect of drying on the quality of low-temperature sausage. *Science and Technology of Food Industry, 35*(18), 843–853.

Guynot, M. E., Sanchis, V., Ramos, A. J., & Marín, S. (2010). Mold-free shelf-life extension of bakery products by active packaging. *Journal of Food Science, 68*(8), 2547–2552.

Holtz, E., Ahrné, L., Rittenauer, M., & Rasmuson, A. (2010). Influence of dielectric and sorption properties on drying behaviour and energy efficiency during microwave convective drying of selected food and non-food inorganic materials. *Journal of Food Engineering, 97*(2), 144–153.

Jafari, M., & Emam-Djomeh, Z. (2007). Reducing nitrite content in hot dogs by hurdle technology. *Food Control, 18*(12), 1488–1493.

Jang, S. J., Kim, H. W., Hwang, K. E., Song, D. H., Kim, Y. J., Ham, Y. K., & Kim, C. J. (2015). Effects of replacing sucrose with various sugar alcohols on quality properties of semi-dried jerky. *Korean Journal for Food Science of Animal Resources, 35*(5), 622–629.

Jangam, S. V. (2016). Recent critical reviews of drying. *Drying Technology, 34*(4), 385.

Kampf, N., & Nussinovitch, A. (2000). Hydrocolloid coating of cheeses. *Food Hydrocolloids, 14*(6), 531–537.

Kanatt, S. R., Chawla, S. P., Chander, R., & Bongirwar, D. R. (2002). Shelf-stable and safe intermediate-moisture meat products using hurdle technology. *Journal of Food Protection, 65*(10), 1628–1631.

Kanatt, S. R., Chawla, S. P., Chander, R., & Sharma, A. (2006). Development of shelf-stable, ready-to-eat (RTE) shrimps (Penaeus indicus) using gamma-radiation as one of the hurdles. *LWT – Food Science and Technology, 39*(6), 621–626.

Karizaki, V. M., Sahin, S., Sumnu, G., Mosavian, M. T. H., & Luca, A. (2013). Effect of ultrasound-assisted osmotic dehydration as a pretreatment on deep fat frying of potatoes. *Food and Bioprocess Technology, 6*(12), 3554–3563.

Khoshakhlagh, K., Hamdami, N., Shahedi, M., & Le-Bail, A. (2014). Quality and microbial characteristics of part-baked Sangak bread packaged in modified atmosphere during storage. *Journal of Cereal Science, 60*(1), 42–47.

Kim, B., Yun, H., Jung, S., Jung, Y., Jung, H., Choe, W., & Jo, C. (2011). Effect of atmospheric pressure plasma on inactivation of pathogens inoculated onto bacon using two different gas compositions. *Food Microbiology, 28*(1), 9–13.

Kowalska, H., Lenart, A., & Leszczyk, D. (2008). The effect of blanching and freezing on osmotic dehydration of pumpkin. *Journal of Food Engineering, 86*(1), 30–38.

Kunová, S., Čuboň, J., Bučko, O., Kačániová, M., Tkáčová, J., Hleba, L., & Lopašovský, Ľ. (2015). Evaluation of dried salted pork ham and neck quality. *Potravinarstvo, 9*(1), 509–514.

Laroussi, M. (2010). Low temperature plasma-based sterilization: Overview and state-of-the-art. *Plasma Processes and Polymers, 2*(5), 391–400.

Lee, D. J. (2009). Structure evolution of wastewater sludge during electroosmotic dewatering. *Drying Technology, 28*(7), 890–900.

Lekjing, S. (2016). A chitosan-based coating with or without clove oil extends the shelf life of cooked pork sausages in refrigerated storage. *Meat Science, 111*, 192–197.

Lespinard, A. R., Bambicha, R. R., & Mascheroni, R. H. (2012). Quality parameters assessment in kiwi jam during pasteurization. Modelling and optimization of the thermal process. *Food and Bioproducts Processing, 90*(4), 799–808.

Li, R., Kou, X., Zhang, L., et al. (2018). Inactivation kinetics of food-borne pathogens subjected to thermal treatments: A review[J]. *International Journal of Hyperthermia, 34*(2), 177–188.

Li, X., Xie, X., Zhang, C.-h., Zhen, S., & Jia, W. (2018). Role of mid- and far-infrared for improving dehydration efficiency in beef jerky drying. *Drying Technology, 36*(3), 283–293.

Lima, M. M. D., Tribuzi, G., Souza, J. A. R. D., Souza, I. G. D., Laurindo, J. B., & Carciofi, B. A. M. (2016). Vacuum impregnation and drying of calcium-fortified pineapple snacks. *LWT – Food Science and Technology, 72*, 501–509.

Lin, T. M., Durance, T. D., & Scaman, C. H. (1999). Physical and sensory properties of vacuum microwave dehydrated shrimp. *Journal of Aquatic Food Product Technology, 8*(4), 41–53.

Lin, X., Luo, C., & Chen, Y. (2016). Effects of vacuum impregnation with sucrose solution on mango tissue. *Journal of Food Science, 81*(6), E1412–E1418.

Ling, J., Teng, Z. S., Lin, H. J., & Wen, H. (2017). Infrared drying kinetics and moisture diffusivity modeling of pork. *International Journal of Agricultural & Biological Engineering, 10*(3), 302–311.

Liu, H., Yang, Z., Jin, G., Quan, Y., Zheng, G., Jin, H., & Li, G. (2013). The development of Yanbian yellow dried beef. *Food Science and Technology, 38*(11), 116–119.

Liu, S., Tang, J., Tadapaneni, R., Yang, R., & Zhu, M. J. (2018). Exponentially increased thermal resistance of *Salmonella* and *Enterococcus faecium* at reduced water activity. *Applied and Environmental Microbiology, 84*(8) e02742–17.

Liu, Y., Sun, Y., Yu, H., Yin, Y., Li, X., & Duan, X. (2016). Hot air drying of purple-fleshed sweet potato with contact ultrasound assistance. *Drying Technology, 35*, 564–576.

Lombard, G. E., Oliveira, J. C., Fito, P., & Andrés, A. (2008). Osmotic dehydration of pineapple as a pre-treatment for further drying. *Journal of Food Engineering, 85*(2), 277–284.

Ma, R., Wang, G., Tian, Y., Wang, K., Zhang, J., & Fang, J. (2015). Non-thermal plasma-activated water inactivation of food-borne pathogen on fresh produce. *Journal of Hazardous Materials, 300*, 643–651.

Maneffa, A. J., Stenner, R., Matharu, A. S., Clark, J. H., Matubayasi, N., & Shimizu, S. (2017). Water activity in liquid food systems: A molecular scale interpretation. *Food Chemistry, 237*, 1133–1138.

Marchiore, N. G., Manso, I. J., Kaufmann, K. C., Lemes, G. F., Pizolli, A. P. D. O., Droval, A. A., & Leimann, F. V. (2017). Migration evaluation of silver nanoparticles from antimicrobial edible coating to sausages. *LWT – Food Science and Technology, 76*, 203–208.

Masegosa, R., Delgado-Adámez, J., Contador, R., Sánchez-Íñiguez, F., & Ramírez, R. (2014). Effect of processing by hydrostatic high pressure of two ready to heat vegetable meals and stability after refrigerated storage. *Food Science and Technology International, 20*(8), 605–615.

Mee-Ngern, B., Lee, S. J., Choachamnan, J., & Boonsupthip, W. (2014). Penetration of juice into rice through vacuum drying. *LWT – Food Science and Technology, 57*(2), 640–647.

Mendonça, K. S. D., Corrêa, J. L. G., Junqueira, J. R. D. J., Pereira, M. C. D. A., & Vilela, M. B. (2016). Optimization of osmotic dehydration of yacon slices. *Drying Technology, 34*(4), 150619113651006.

Misra, N. N., Tiwari, B. K., Raghavarao, K. S. M. S., & Cullen, P. J. (2011). Nonthermal plasma inactivation of food-borne pathogens. *Food Engineering Reviews, 3*(3–4), 159–170.

Moreno, J., Gonzales, M., Zúñiga, P., Petzold, G., Mella, K., & Muñoz, O. (2016). Ohmic heating and pulsed vacuum effect on dehydration processes and polyphenol component retention of osmodehydrated blueberries (cv. Tifblue). *Innovative Food Science & Emerging Technologies, 36*, 112–119.

Moreno, J., Simpson, R., Estrada, D., Lorenzen, S., Moraga, D., & Almonacid, S. (2011). Effect of pulsed-vacuum and ohmic heating on the osmodehydration kinetics, physical properties and microstructure of apples (cv. Granny Smith). *Innovative Food Science & Emerging Technologies, 12*(4), 562–568.

Neri, L., Biase, L. D., Sacchetti, G., Mattia, C. D., Santarelli, V., Mastrocola, D., & Pittia, P. (2016). Use of vacuum impregnation for the production of high quality fresh-like apple products. *Journal of Food Engineering, 179*, 98–108.

Nevena, M., Gordana, K., Ljubinko, L., Mariana, P., & Tatjana, K. (2008). Mass transfer during osmotic dehydration of apple and carrot in sugar beet molasses. *časopis za procesnu tehniku i energetiku u poljoprivredi / ptep, 12*(4), 211–214.

Ngamjit, L., & Sanguansri, C. (2009). Influence of osmodehydrofreezing with different sugars on the quality of frozen rambutan. *International Journal of Food Science and Technology, 44*(11), 2183–2188.

Nowacka, M., Tylewicz, U., Laghi, L., Rosa, M. D., & Witrowa-Rajchert, D. (2014). Effect of ultrasound treatment on the water state in kiwifruit during osmotic dehydration. *Food Chemistry, 144C*(2), 18–25.

Oliveira, F. I. P., Rodrigues, S., & Fernandes, F. A. N. (2012). Production of low calorie Malay apples by dual stage sugar substitution with Stevia-based sweetener[J]. *Food and Bioproducts Processing, 90*(4), 713–718.

Olmo, A. D., Calzada, J., & Nuñez, M. (2014). Effect of high pressure processing and modified atmosphere packaging on the safety and quality of sliced ready-to-eat “lacón”, a cured–cooked pork meat product. *Innovative Food Science & Emerging Technologies, 26*, 134–142.

Ozkahraman, B. C., Sumnu, G., & Sahin, S. (2016). Effect of different flours on quality of legume cakes to be baked in microwave-infrared combination oven and conventional oven. *Journal of Food Science and Technology, 53*(3), 1567–1575.

Paes, S. S., Stringari, G. B., & Laurindo, J. B. (2007). Effect of vacuum and relaxation periods and solution concentration on the osmotic dehydration of apples. *International Journal of Food Science and Technology, 42*(4), 441–447.

Panades, G., Castro, D., Chiralt, A., Fito, P., Nuñez, M., & Jimenez, R. (2008). Mass transfer mechanisms occurring in osmotic dehydration of guava. *Journal of Food Engineering, 87*(3), 386–390.

Pattanapa, K., Therdthai, N., Chantrapornchai, W., & Zhou, W. B. (2010). Effect of sucrose and glycerol mixtures in the osmotic solution on characteristics of osmotically dehydrated mandarin cv. (Sai-Namphaung). *International Journal of Food Science and Technology, 45*(9), 1918–1924.

Peng, J., Tang, J., Barrett, D. M., Sablani, S., Anderson, N., & Powers, J. R. (2017). Thermal pasteurization of ready-to-eat foods and vegetables: Critical factors for process design and effects on quality. *Critical Reviews in Food Science and Nutrition, 57*(14), 2970–2995.

Pereira, N. R., Marsaioli, A., & Ahrné, L. M. (2007). Effect of microwave power, air velocity and temperature on the final drying of osmotically dehydrated bananas. [Article]. *Journal of Food Engineering, 81*(1), 79–87.

Phongsomboon, P., & Intipunya, P. (2009). Comparative study on drying of osmotic treated carrot slices. *Asian Journal of Food and Agro-Industry, 2*(04), 448–456.

Puligundla, P., Choi, S., & Mok, C. (2017). Microbial Decontamination of Gwamegi (Semi-dried Pacific Saury) using Corona Discharge Plasma Jet, Including Physicochemical and Sensory Evaluation. *Journal of Aquatic Food Product Technology, 27*(3), 274–283.

Que, T. (2013). Effect of Different Drying Methods on the Protein and Product Quality of Hairtail fish Meat Gel. *Drying Technology, 31*(13–14), 1707–1714.

Riadh, M. H., Ahmad, S. A. B., Marhaban, M. H., & Soh, A. C. (2015). Infrared heating in food drying: An overview. *Drying Technology, 33*(3), 322–335.

Ribeiro, G. P., Villas-Bôas, J. K., Spinosa, W. A., & Prudencio, S. H. (2018). Influence of freezing, pasteurization and maturation on Tiúba honey quality. *LWT – Food Science and Technology, 90*, 607–612.

Rizzo, V., Clifford, M. N., Brown, J. E., Siracusa, L., & Muratore, G. (2016). Effects of processing on the polyphenol and phenolic acid content and antioxidant capacity of semi-dried cherry tomatoes (Lycopersicon esculentum M.). *Journal of the Science of Food and Agriculture, 96*(6), 2040–2046.

Rodríguez, M., Medina, L. M., & Jordano, R. (2000). Effect of modified atmosphere packaging on the shelf life of sliced wheat flour bread. *Molecular Nutrition & Food Research, 44*(4), 247–252.

Rupasinghe, V., Handunkutti, P., Joshi, A. P. K., & Pitts, N. L. (2010). *Non-fried apple food products and processes for their preparation.* (US20100159082).

Sanguinetti, A. M., Caro, A. D., Scanu, A., Fadda, C., Milella, G., Catzeddu, P., & Piga, A. (2016). Extending the shelf life of gluten-free fresh filled pasta by modified atmosphere packaging. *LWT – Food Science and Technology, 71*, 96–101.

Santacruzvázquez, V. (2007). Application of osmotic dehydration processes to produce apple slices enriched with -Carotene. *Drying Technology, 26*(10), 1265–1271.

Schmidt, F. C., Bam, C., & Laurindo, J. B. (2008). Salting operational diagrams for chicken breast cuts: Hydration-dehydration. *Journal of Food Engineering, 88*(1), 36–44.

Schröder, U. (2010). Changes in phosphate and water content during processing of salted Pacific cod (Gadus macrocephalus). *Journal of Aquatic Food Product Technology, 19*(1), 16–25.

Segat, A., Misra, N. N., Cullen, P. J., & Innocente, N. (2016). Effect of atmospheric pressure cold plasma (ACP) on activity and structure of alkaline phosphatase. *Food and Bioproducts Processing, 98*, 181–188.

Selby, T. L., Berzins, A., Gerrard, D. E., Corvalan, C. M., Grant, A. L., & Linton, R. H. (2006). Microbial heat resistance of Listeria monocytogenes and the impact on ready-to-eat meat quality after post-package pasteurization. *Meat Science, 74*(3), 425–434.

Sergio, L., Cantore, V., Spremulli, L., Pinto, L., Baruzzi, F., Venere, D. D., & Boari, F. (2017). Effect of cooking and packaging conditions on quality of semi-dried green asparagus during cold storage. *LWT – Food Science and Technology, 89*, 712–718.

Sevenich, R., Rauh, C., & Knorr, D. (2016). A scientific and interdisciplinary approach for high pressure processing as a future toolbox for safe and high quality products: A review. *Innovative Food Science & Emerging Technologies, 38*, 65–75.

Silva, K. S., Fernandes, M. A., & Mauro, M. A. (2014). Effect of calcium on the osmotic dehydration kinetics and quality of pineapple. *Journal of Food Engineering, 134*(134), 37–44.

Simal, S., Benedito, J., Sánchez, E. S., & Rosselló, C. (1998). Use of ultrasound to increase mass transport rates during osmotic dehydration. *Journal of Food Engineering, 36*(3), 323–336.

Smith, G., Hole, M., & Hanson, S. W. (1990). Assessment of lipid oxidation in indonesian salted-dried marine catfish (Arius thalassinus). *Journal of the Science of Food and Agriculture, 51*(2), 193–205.

Soliva-Fortuny, R. C., Elez-MartíNez, P., Sebastián-Calderó, M., & MartíN-Belloso, O. (2004). Effect of combined methods of preservation on the naturally occurring microflora of avocado purée. *Food Control, 15*(1), 11–17.

Song, H. P., Kim, B., Choe, J. H., Jung, S., Moon, S. Y., Choe, W., & Jo, C. (2009). Evaluation of atmospheric pressure plasma to improve the safety of sliced cheese and ham inoculated by 3-strain cocktail Listeria monocytogenes. *Food Microbiology, 26*(4), 432–436.

Speckhahn, A., Srzednicki, G., Desai, D. K., & Devahastin, S. (2010). Drying of beef in superheated steam. *Drying Technology, 28*(9), 1072–1082.

Stekelenburg, F. K. (2003). Enhanced inhibition of Listeria monocytogenes in Frankfurter sausage by the addition of potassium lactate and sodium diacetate mixtures. *Food Microbiology, 20*(1), 133–137.

Stoica, M., Alexe, P., & Mihalcea, L. (2014). Atmospheric cold plasma as new strategy for foods processing – An overview. *Innovative Romanian Food Biotechnology, 96*(1), 88–90.

Stratakos, A. C., Delgado-Pando, G., Linton, M., Patterson, M. F., & Koidis, A. (2015). Synergism between high-pressure processing and active packaging against Listeria monocytogenes in ready-to-eat chicken breast. *Innovative Food Science & Emerging Technologies, 27*, 41–47.

Stratakos, A. C., Linton, M., Patterson, M. F., & Koidis, A. (2015). Effect of high-pressure processing on the shelf life, safety and organoleptic characteristics of lasagne ready meals during storage at refrigeration and abuse temperature. *Innovative Food Science & Emerging Technologies, 30*, 1–7.

Su, Y., Zhang, M., & Mujumdar, A. S. (2015). Recent developments in smart drying technology. *Drying Technology, 33*(3), 260–276.

Sun, B., Zhao, Y., Yu, J., Ling, J., Shang, H., & Liu, Z. (2017). The combined efficacy of superchilling and high CO_2 modified atmosphere packaging on shelf life and quality of swimming crab (Portunus trituberculatus). *Journal of Aquatic Food Product Technology, 26*(6), 655–664.

Suppakul, P., Thanathammathorn, T., Samerasut, O., & Khankaew, S. (2016). Shelf life extension of “fios de ovos”, an intermediate-moisture egg-based dessert, by active and modified atmosphere packaging. *Food Control, 70*, 58–63.

Syamaladevi, R. M., Tang, J., Villa-Rojas, R., Sablani, S., Carter, B., & Campbell, G. (2016). Influence of water activity on thermal resistance of microorganisms in low-moisture foods: A review. *Comprehensive Reviews in Food Science and Safety, 15*, 353–370.

Tanaka, T., Fujihara, K., Jami, M. S., & Iwata, M. (2014). Constant-current electroosmotic dewatering of superabsorbent hydrogel. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 440*(2), 116–121.

Taylor, M. H., Tsai, H., Rasco, B., Tang, J., & Zhu, M. J. (2018). Stability of Listeria monocytogenes in wheat flour during extended storage and isothermal treatment. *Food Control, 91*, 434–439.

Tenhet, V., Finne, G., & Toloday, D. (1981). Penetration of sodium tripolyphosphate into fresh and Prefrozen peeled and deveined shrimp. *Journal of Food Science, 46*(2), 344–349.

Thippeswamy, L., Venkateshaiah, B. V., & Patil, S. B. (2011). Effect of modified atmospheric packaging on the shelf stability of paneer prepared by adopting hurdle technology. *Journal of Food Science and Technology, 48*(2), 230–235.

Torti, M. J., Sims, C. A., Adams, C. M., & Sarnoski, P. J. (2016). Polysaccharides as alternative moisture retention agents for shrimp. *Journal of Food Science, 81*(3), S728–S735.

Tortoe, C. (2010). A review of osmodehydration for the food industry. *African Journal of Food Science, 4*, 303–324.

Tylewicz, U., Romani, S., Widell, S., & Galindo, F. G. (2013). Induction of vesicle formation by exposing apple tissue to vacuum impregnation. *Food and Bioprocess Technology, 6*(4), 1099–1104.

Vermeulen, A., Daelman, J., Van, S. J., & Devlieghere, F. (2012). Screening of different stress factors and development of growth/no growth models for Zygosaccharomyces rouxii in modified Sabouraud medium, mimicking intermediate moisture foods (IMF). *Food Microbiology, 32*(2), 389–396.

Vermeulen, A., Marvig, C. L., Daelman, J., Xhaferi, R., Nielsen, D. S., & Devlieghere, F. (2015). Strategies to increase the stability of intermediate moisture foods towards Zygosaccharomyces rouxii: The effect of temperature, ethanol, pH and water activity, with or without the influence of organic acids. *Food Microbiology, 45*, 119–125 *Pt A*(Pt A).

Viana, A. D., Corrêa, J. L. G., & Justus, A. (2014). Optimisation of the pulsed vacuum osmotic dehydration of cladodes of fodder palm. *International Journal of Food Science and Technology, 49*(3), 726–732.

Wang, D., Zhang, M., Wang, Y., & Martynenko, A. (2018). Effect of pulsed-spouted bed microwave freeze drying on quality of apple cuboids. *Food and Bioprocess Technology, 11*(5), 941–952.

Wang, L., Pang, X. F., Wang, G. Z., & Xiao-Bo, H. U. (2012). The drying process optimization of beef jerky. *Science and Technology of Food Industry, 33*(9), 328–332.

Wang, L., Zhao, L., Yuan, J., & Jin, T. Z. (2015). Application of a novel antimicrobial coating on roast beef for inactivation and inhibition of Listeria monocytogenes during storage. *International Journal of Food Microbiology, 211*, 66–72.

Wang, W., Cao, z., sun, Y., & Qin, W. (2012). Effect of antiseptic compound film on the quality of preserved meat. *Food Science, 33*(2), 276–279.

Wang, Z. F., Fang, S. Z., & Hu, X. S. (2009). Effective diffusivities and energy consumption of whole fruit Chinese jujube (Zizyphus jujuba Miller) in microwave drying. *Drying Technology, 27*(10), 1097–1104.

Wieczyńska, J., & Cavoski, I. (2018). Antimicrobial, antioxidant and sensory features of eugenol, carvacrol and trans-anethole in active packaging for organic ready-to-eat iceberg lettuce. *Food Chemistry, 259*, 251–260.

Wojdyło, A., Figiel, A., Lech, K., Nowicka, P., & Oszmiański, J. (2014). Effect of convective and vacuum–microwave drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. *Food and Bioprocess Technology, 7*(3), 829–841.

Wojdyło, A., Figiel, A., Legua, P., Lech, K., Carbonellbarrachina, Á. A., & Hernández, F. (2016). Chemical composition, antioxidant capacity, and sensory quality of dried jujube fruits as affected by cultivar and drying method. *Food Chemistry, 207*, 170–179.

Xie, J., & Zhao, Y. (2009). Nutritional enrichment of fresh apple (Royal Gala) by vacuum impregnation. *International Journal of Food Sciences and Nutrition, 96*(54), 387–398.

Xie, X., Li, X., Zhang, C., Jia, W., Li, Y., Sun, H., & Mu, G. (2013). Combined mid-infrared and hot air drying reduces energy-consumption and improves quality of jerky. *Transactions of the Chinese Society of Agricultural Engineering, 29*(23), 217–226.

Yoshida, H., Yoshikawa, T., & Kawasaki, M. (2013). Evaluation of suitable material properties of sludge for electroosmotic dewatering. *Drying Technology, 31*(7), 775–784.

Yu, D., Li, P., Xu, Y., Jiang, Q., & Xia, W. (2016). Physicochemical, microbiological, and sensory attributes of chitosan-coated grass carp (Ctenopharyngodon Idellus) fillets stored at 4°C. *International Journal of Food Properties, 20*, 390–401.

Yun, H. J., Binna, K., Jung, S., Kruk, Z. A., Danbee, K., Wonho, C., & Cheorun, J. (2010). Inactivation of Listeria monocytogenes inoculated on disposable plastic tray, aluminum foil, and paper cup by atmospheric pressure plasma. *Food Control, 21*(8), 1182–1186.

Zarein, M., Samadi, S. H., & Ghobadian, B. (2015). Investigation of microwave dryer effect on energy efficiency during drying of apple slices. *Journal of the Saudi Society of Agricultural Sciences, 14*(1), 41–47.

Zhang, J., Min, Z., Liang, S., & Fang, Z. (2007). Microwave-vacuum heating parameters for processing savory crisp bighead carp (Hypophthalmichthys nobilis) slices. *Journal of Food Engineering, 79*(3), 885–891.

Zhao, J., Hu, R., Xiao, H., Yang, Y., Liu, F., Gan, Z., & Ni, Y. (2014a). Osmotic dehydration pretreatment for improving the quality attributes of frozen mango: Effects of different osmotic solutes and concentrations on the samples. *International Journal of Food Science and Technology, 49*(4), 960–968.

Zhao, J. H., Hu, R., Xiao, H. W., Yang, Y., Liu, F., Gan, Z. L., & Ni, Y. Y. (2014b). Osmotic dehydration pretreatment for improving the quality attributes of frozen mango: Effects of different osmotic solutes and concentrations on the samples. *International Journal of Food Science and Technology, 49*(4), 960–968.

Zhao, Y., & Xie, J. (2004). Practical applications of vacuum impregnation in fruit and vegetable processing. *Trends in Food Science and Technology, 15*(9), 434–451.