Food Science and Applied Biotechnology, 2023, **6**(2), 200-214

UFT Academic Publishing House, Plovdiv

Food Science and Applied Biotechnology
e-ISSN: 2603-3380

Journal home page: www.ijfsab.com
https://doi.org/10.30721/fsab2023.v6.i2

OPEN ACCESS

Review Article

Application of vacuum impregnation in muscle foods

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Abstract

The vacuum impregnation technique has a key role in mass transfer through the pores of animal or vegetable tissues by using different pressures. Removing the internal liquids and gases trapped in the capillaries by applying vacuum pressure and replacing them with the desired solution after the atmospheric pressure is restored is possible. The technique is aimed to impregnate chemical/organic compounds into the capillary structure of biological tissues by utilizing the empty fractions of foods. Vacuum impregnation is used for various products in the food industry to ease the impregnation of ingredients e.g. salt, binding agents, coating materials, antioxidant or antimicrobial agents, etc. To successfully apply this technique, it is important to know the characteristics of the food and to choose the application parameters appropriately. The processing efficiency and quality of the food to be processed should be considered carefully. Purpose-oriented processes are important in the preparation of materials. Vacuum impregnation has excellent potential for improving the overall quality and increasing the shelf life of meat and fishery products.

Keywords

vacuum impregnation, meat and marine products, novel technique, marination, brining, coating

Abbreviations

DRP – deformation relaxation phenomenon; HDM – hydrodynamic mechanism; SEM – scanning electron microscopy; TBARS – thiobarbituric acid reactive substances; TEM – transmission electron microscopy; TVB-N – total volatile basic nitrogen; VI – Vacuum impregnation; WHC – water holding capacity

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Article history:
Received 17 April 2023
Reviewed 22 May 2023
Accepted 17 July 2023
Available on-line 11 October 2023

https://doi.org/10.30721/fsab2023.v6.i2.271

Introduction

Different techniques are being investigated to provide healthy food while improving characteristics and sensory attributes. One of the food processing techniques is vacuum impregnation (VI) based on diffusion. Vacuum impregnation was developed more than 25 years ago by Fito and Pastor (1994). Researchers verified that mass transfer increased when VI was applied to apple slices (8 mm thick) in an isotonic saccharose solution. Moreover, they explained the flow is governable that can also be used as a procedure for the design of new products (Fito and Pastor 1994). Vacuum impregnation is based on the transfer of intracellular gas or liquid from the pores to the external solution through the hydrodynamic mechanism as a consequence of the pressure gradient. It accelerates and eases food processing such as osmotic dehydration. VI also causes solid matrix deformation and relaxation along with gas or liquid transfer due to the changes in pressure (de Lima et al. 2016; Sulistyawati et al. 2018). VI applications are used for different purposes in the food industry; to shorten the processing time by reducing the duration of technological and preparatory treatments, modifying the composition of food to be processed, and carrying various substances into the product which improves the nutritional and sensory quality (Kobus et al. 2021).

The penetration of solutions into food pores at low temperatures preserves the heat-sensitive bioactive components. VI has the potential to incorporate bioactive compounds into the food matrix to improve food properties. These compounds provide several advantages, such as the increase in nutritional value (e.g., enrichment with polyphenols, probiotics, or micronutrients), the extension of shelf life (e.g., reduction of pH), or the improvement of sensory attributes (e.g., flavor enhancer). Vacuum impregnation is an operation frequently applied in fruit and vegetable processing (Radziejewska-Kubzdela et al. 2014; Panayampadan et al. 2022).

Vacuum impregnation is the new method used in salting/marination/dehydration/enrichment, etc., based on food microstructural properties (Dinçer and Erbaş 2018). This technique is a controlled hydrodynamic process that accelerates and eases mass transfer during processing through the capillary structure of the food matrix (Kirmizikaya and Çinar 2018). It has many advantages such as the utilization in fresh food processing, enrichment/fortification of foods with minerals and vitamins, use as a pre-treatment in dehydration/freezing/canning/frying processes, modification of products formulation, preserving natural and many heat-sensitive ingredients, inhibition of discoloration by elimination of oxygen, penetration of antimicrobial and antioxidant agents into the product and enhancing quality (Senturk Parreidt et al. 2018). Simultaneously, incorporating antioxidants, vitamins, and other bioactive compounds through VI would enhance the beneficial health properties (Kolev 2022). Using VI to develop healthier meat products is an innovative strategy. This review aims to determine the potential of using vacuum impregnation in different steps of processing meat and marine products to extend shelf life, improve quality and sensory properties, and shorten process duration.

Vacuum Impregnation Mechanism

This method was first applied as a vacuum osmotic dehydration to accelerate water loss during the immersion of fruits and vegetables in a hypertonic solution and provided the solution inlet into the tissue (Dinçer and Erbaş 2018). VI of porous food involves removing the gas or liquid normally occupying pores and replacing it with an external solution. Impregnation occurs due to the hydrodynamic mechanism created by the pressure gradient (Kirmizikaya and Çinar 2018). A model was created by considering tissue pores as fixed diameter ideal cylinders against the solution. The internal pressure of the pore (pi), the capillary pressure (pc), and the pressure acting on the liquid (pl) (expressed in Pa) cause the change of the pore volume fraction by liquid. The capillary pressure is related to the properties of the pores and is defined by the Young-Laplace equation 1 (Dullien 2012):

$$Pc = \sigma \, [\, 1/r_1 + 1/r_2] \cos\theta \qquad (1)$$

σ - represents the interfacial tension ($N.m^{-1}$),

r_1 and r_2 - represent the principal radii (m) of the pores, and θ is the contact angle (rad).

The vacuum impregnation process typically consists of 4 steps (Fig. 1):

1. Immersion of the solid matrix in a tank containing the liquid phase

2. Vacuum ($p_l < p_{atm}$) is employed in the system for a short time (t_1) in the closed tank, which leads to expanding the gas in the pores ($p_i > p_l + p_c$). Then gas and some liquid leave through the pores.

3. When the pressure of the pores is equal to the system pressure, $pi = p_l$ ($p_l < p_{atm}$) penetration of liquid will promote into the capillary tubes as a result of the hydrodynamic mechanism, and the pressure of the capillary structure will rise slowly.

4. Atmospheric pressure ($p_l = p_{atm}$) is restored in the tank for a time (t_2). The increment of the pressure in the capillary structure will lead to a significant decrease in the volume of gas remaining in the pores and will flow the external solution into the porous structure (Kirmizikaya and Çinar 2018).

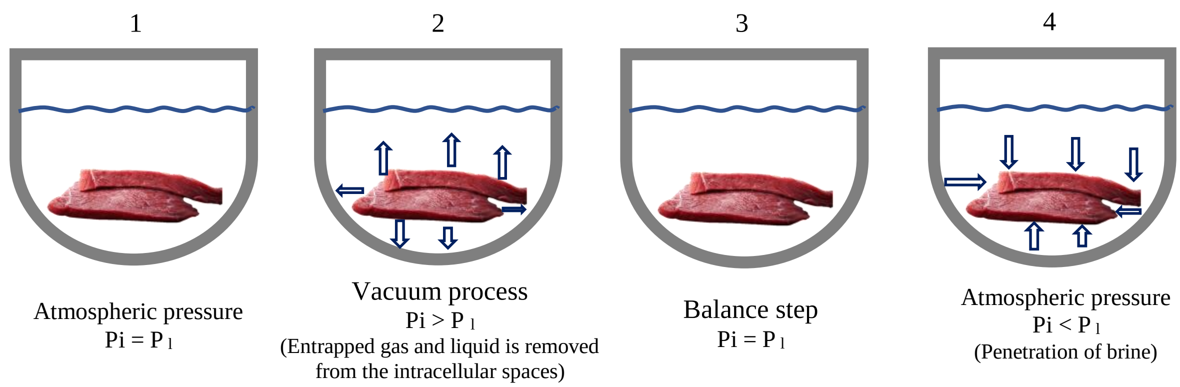

Figure 1. Steps of vacuum impregnation process.

The Characteristics of the Equipment

As shown in Fig. 2, the experimental setup for vacuum impregnation consists of a vacuum pump connected to a stainless steel chamber with a jacket. The temperature within the chamber is regulated by circulating chilled water in the jacket through a thermostatic bath. The pressure inside the chamber is monitored through the utilization of a pressure sensor. To regulate and manipulate the pressure, an electro-valve is incorporated within the chamber. This valve empowers the operator to interrupt the vacuum and restore the atmospheric pressure conditions. There is a tank containing the external solution (e.g., brine) and the immersed porous food. The VI technique is accomplished by applying vacuum pressure in a tank for a short time and afterward restoring the atmospheric pressure while the product remains immersed. Generally, porous food is sliced or chopped into smaller sizes before placing in the tank. The capacity of the equipment depends on the volume of solution and food (Bampi et al. 2016; Zhao et al. 2019). In applications of VI in meat and seafood industry, vacuum pressure is generally selected in the range of 35-650 mmHg; vacuum time is between 1-15 min and restoration time is in the range of 5-30 min (restoration time can be longer depending on the food structure) (Kırmızıkaya and Çınar 2018).

Factors that Affect Vacuum Impregnation

The success of the VI applications depends on intrinsic (e.g., structural and mechanical properties of the food) and extrinsic factors (e.g., properties of external solution, duration, temperature, pressure, pressure steps, etc.) (Kırmızıkaya and Çınar 2018). Food properties such as mechanical properties, surface area, thickness, porosity, pore size, shape, and type of fluid-like gas or liquid in the pores affect mass transfer rate (De Lima et al. 2016; Leal-Ramos et al. 2018; Sulistyawati et al. 2018). Panarese et al. (2013) emphasized that cell morphology, intercellular forces, and pore diameters are effective along with raw material properties. The structure is affected by many factors such as variety and type, maturity, geography, and climate (Yılmaz and Bilek 2017). For this reason, the suitability of the food for VI processing should be determined and optimized for process parameters (Panarese et al. 2013).

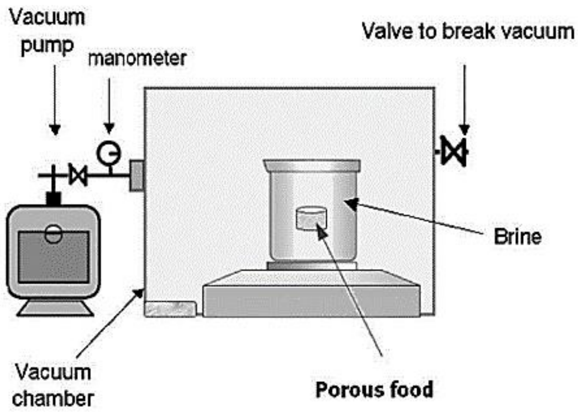

Figure 2. Experimental equipment used for vacuum impregnation. Adapted from (Hofmeister et al. 2005)

It has been indicated that the process efficiency depends on factors such as vacuum pressure, duration, temperature as well as food properties (De Lima et al. 2016; Sulistyawati et al. 2018). The concentration of the immersed solution, viscosity, temperature, type of solvent, molecular weight, and solution-food ratio influence the process yield. The isotonic solution causes no change in the cell, while the hypotonic solution leads cells to swell due to the penetrated solution. On the contrary, a hypertonic solution forces cells to lose water and shrink. Hypertonic solutions are used in osmotic dehydration processes, while isotonic solutions are preferred in the enrichment process to limit the transition from food (Yılmaz and Bilek 2017; Kirmizikaya and Çinar 2018). It has been shown that high salt concentrations lead to an increase the muscle fiber contraction, large extracellular spaces, and an increment in the rate of salt diffusion. In addition, the prolongation of the salting time causes enhancement in the muscle fiber contraction and salt content. However, if salt content exceeds the threshold level (4.5 M) there would be a low yield due to strong protein-protein interactions (Jiang et al. 2019). It is known that temperature affects mass transfer kinetics. It has been determined that increment in temperature increases mass transfer by reducing the viscosity of the solution, and the mixing process also has an effect on the mass transfer rate due to creating turbulent flow (Yılmaz and Bilek 2017; Kirmizikaya and Çinar 2018).

Using VI in Meat and Seafood Industry

In the meat and seafood industry VI technique is used alone or as a pre-treatment in the salting, freezing, drying, coating, and fortification processes. The salting process is employed in two ways, dry salting and wet salting. Dry salting is carried out by covering meat cuts with salt, whereas wet salting is applied by immersion the meat in brine and providing the salt transfer from brine to meat. The salting process of large pieces of meat is usually slow and can take several days due to the low rate of salt diffusion at low temperatures to ensure food safety during processing (Bampi et al. 2016). Vacuum impregnation is a technique that shortens the salting period.

Dehydration is an efficient method to extend shelf life by reducing water activity (a_w). However, conventional hot air dehydration causes negative changes in the mechanical, chemical, and sensory properties and nutritive values of products. The combination of osmotic dehydration with VI has been recognized as an excellent solution to increase mass transfer rate and preserve physicochemical properties and nutritional values. Therefore, VI is used as a pre-processing step, especially for drying technology in the meat and seafood industry.

VI can modify the food formulation and develop new products (Le and Konsue 2021). Recent studies have shown that VI technique has a vital role in adding components such as vitamins, minerals, antioxidants, probiotics, and prebiotics to extend the shelf life and prevent nutrient losses during food processing. According to the literature, using VI technique in foods has increased the number of nutrients such as calcium, beet-derived phenolic compounds, calcium, vitamin C and vitamin E and rosemary essential oil, etc. However, some studies aimed to enrich; others aimed to produce a minimally processed product (Duarte-Correa et al. 2020).

The tenderness of the meat is one of the most essential properties affecting the acceptability of consumers (Demir et al. 2021). Marination improves tenderness and color, enhances flavor, increases juiciness, reduces off-flavors, and provides meat quality through contact between brine and meat by dipping, injection, or tumbling. In addition, it leads to achieving high yields and long shelf life due to the increment of marinade uptake (Demir et al. 2021). The advantages of using VI technique for the marinating process are high yield and short marinating time (Larrazábal-Fuentes et al. 2009).

Freshness and safety have a vital role in the quality characteristics of meat products. To prevent the deterioration of quality, VI technique has been effectively applied to incorporate coating solution into a porous solid matrix and has created a thicker, homogeneous coating. Hence, the rise in the production of edible coatings offers an environmentally-friendly solution to the issue of escalating polymer waste within the ecosystem (Vlahova-Vangelova et al. 2022). Senturk Parreidt et al. (2018) have indicated that VI successfully increased the amount of coating solution uptake. This result showed that vacuum application and duration of atmospheric restoration were more effective than the vacuum level. The research concluded that VI technique has more effect on quality characteristics (color and texture) than traditional methods and can be used for coating applications (Senturk Parreidt et al. 2018; Soares et al. 2018). VI is also used as a step in the freezing, canning, and drying processes.

Effects of Vacuum Impregnation on Meat Products and Seafood

Mass transfer rate, processing time and processing yield. Mass transfer rate during VI depends on the properties of the pores. Therefore, tissues with different porosity, pore diameters, and shape show different mass transfer rates (Panarese et al. 2013). The success of vacuum impregnation requires efficiently eliminating gas and liquid from the tissue during the application of vacuum so that the tissue is filled when atmospheric pressure is restored. Fig. 3 shows that the application of VI increases the diffusion rate by pressure gradient and rise process yield by enhancing the contact area between the external solution and tissue. The hydrodynamic mechanism (HDM) ensures the gas/liquid occupying the pores of food moves away quickly at the vacuum pressure, creates large spaces, combines the pressure difference between the inside and outside of the cell and the capillary effect, and accelerates the external solution inlet. The deformation relaxation phenomenon (DRP) accelerates the shallow liquid inlet into the food and provides its homogeneous distribution due to expanding the structure and cell space in the vacuum system. Therefore, vacuum impregnation is an excellent method to increase process efficiency. The salt content was found higher in VI-treated samples that were cured with the same salt concentration and time compared to the non-VI-treated samples, and the reason for this phenomenon was described by the principle of HDM and DRP (Wang et al. 2016; Shen et al. 2020). The application of vacuum impregnation during the wet curing process reduces the time of meat slice processing. This is due to the higher salt uptake rate, which results from the synergistic contribution of the hydrodynamic mechanism to the osmotic and diffusion agents involved in the process. However, salt uptake of meat is restricted when marinated with acids (Bampi et al. 2016; Figueroa et al. 2020). Tomac et al. (2020) have shown that VI significantly affected mass transfer kinetics in salted hake (*Merluccius hubbsi*). Reaching the desired salt concentration in the product is achieved in a short time due to accelerating salt uptake. Agustinelli and Yeannes (2015) reported that the mass transfer rate of caballa fish (*Scomber japonicus*) during immersion in 12 g NaCl /100 mL brine at 14°C and atmospheric pressure was different from the values found for Argentine hake (*Merluccius hubbsi)*. They have explained that it is in consequence of the high lipid content in caballa fish, which is created a barrier to mass transfer kinetics. It has been shown that the mass transfer rate increases in parallel with salt concentration; however, inversely with the water content (Agustinelli and Yeannes 2015; Tomac et al. 2020).

Oxidation reactions. Lipid oxidation is one of the important criteria that plays an important role in the quality of meat and seafood. Oxidation products can react with food ingredients, causing undesirable color, taste, and nutritional value changes (Demir et al. 2021). Cooked products have a higher degree of lipid oxidation than uncooked products. While oxidation causes loss in sensory properties such as nutritional value, color, and flavor of food, it creates functional disorders in some specific proteins. It has been thought that moisture loss and temperature during the cooking process trigger the acceleration of oxidation reactions (Çelik 2019).

Analysis of thiobarbituric acid reactive substances (TBARS) is the most common method to determine the lipid oxidation secondary products as mg malonaldehyde/kg (mg MDA/kg) (Serdaroğlu et al. 2022).

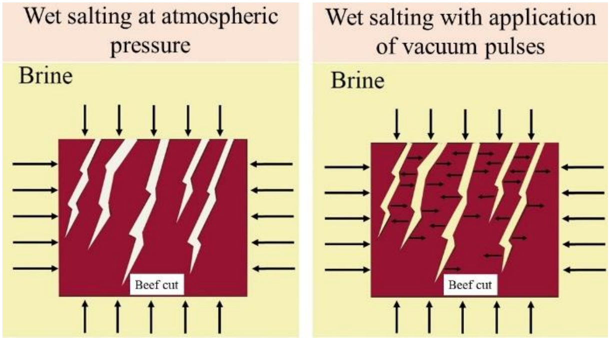

Figure 3. Differences in mass transfer between salting at atmospheric pressure and application of vacuum pulses. Adapted from (Bampi et al. 2016)

Applying VI as pre-treatment to beef marination with onion juice for 20, 40, and 60 min resulted in higher TBARS values in uncooked samples than control (Demir et al. 2021). Smoked salmon treated with VI technique showed 0.18±0.04 mg MDA.kg^{-1} at day 0, and no significant changes were observed during the first 15-20 days. . A significant increase was observed in TBARS values from the 20th day onward and reached 0.40 mg MDA.kg^{-1} level on the 30th storage day. However, TBARS values were below the levels established by other authors for fish rancidity - 0.58 mg MDA.kg^{-1} (Martinez et al. 2007), which showed that lipid oxidation was not particularly significant in the cases studied (Bugueño et al. 2003).

Lipid oxidation products are known to promote protein oxidation. Lipid radicals (peroxide radicals), hydroperoxides, and lipid oxidation final products cause protein oxidation in muscle tissue. Therefore, in parallel with lipids, the damage also occurs in protein structure. Protein carbonyls and protein hydroperoxides form as a consequence of the amino acid side chain modification (Ergezer et al. 2016). Total carbonyl is the main indicator of protein oxidation (Liu et al. 2019).

According to Shen et al. (2020), the carbonyl content was lower in VI-treated meat in the brine with the same salt concentration than in the samples non-VI-treated. They have indicated that both the salt concentration and salting period were effective on carbonyl formation. It was observed that the carbonyl content increased significantly as a result of increasing salt concentrations and the salting period. Antioxidant protection of proteins is reduced through increasing salt concentration and time, leading to the release of pro-oxidant and oxidase (Du et al. 2018). According to previous studies, high salt concentrations have contributed to increasing enzymatic activity (Stoknes et al. 2005). TBARS values and carbonyl content were investigated in fish fillets coated with fish gelatin, grape seed extract, chitosan, and different extracts (pomegranate peel, grape seed, and green tea extracts) using the VI technique. TBARS value of fish slices coated with chitosan and pomegranate peel, grape seed, and green tea extracts was determined at an initial level of 0.35 mg MDA.kg^{-1}, and carbonyl content was reduced in fillets coated with fish gelatin and grape seed extract (Zhao et al. 2019; Zhao et al. 2021).

Other physicochemical properties. Water holding capacity (WHC) is a critical quality characteristic of meat and has a significant effect on juiciness, texture, and mouthfeel (Jiang et al. 2019). The concentration of the solution, VI duration, and WHC indicated a significant association. Shen et al. (2020) reported that WHC increased at the beginning during the VI-assisted salting process, then decreased due to breaking the connective tissue when the muscle swelled. They have explained that extracellular spaces may form channels for drip loss and reduce WHC. It has been shown that minimum and maximum muscle swell occurred when salt concentration reached 0.1 M and 1 M, respectively. The microstructural modification was examined by scanning delectron microscopy (SEM) and transmission electron microscopy (TEM) analyses; it has been indicated that proper salting causes the extraction of myofibrillar proteins, swells the filament lattice, and enhances WHC. However, muscle contraction occurs when the salt concentration is more than 4.5 M. High salt concentration increases protein-protein interactions through hydrophobic association, resulting in protein aggregation/denaturation and decrement of WHC in muscle (Jiang et al. 2019; Shen et al. 2020).

Limited studies have been conducted on the effects of VI on the textural properties of meat. Pre-treatment of samples by VI is shown a reduction in firmness compared to conventional samples, which can be related to the microstructural changes in meat fibers (Demir et al. 2021). Investigation of using VI in moisture-enhance methods in meat has indicated that brine gain was similar to injection methods or the application of high salt and sodium phosphate concentration which increases sodium levels. VI provides good water distribution in uncooked meat and significantly affects tenderness. It has been shown that there were no statistical differences in springiness and chewiness of VI-treated beef samples compared to non-VI-treated samples (Leal-Ramos et al. 2018). Generally, the hardness of VI-treated meat samples decreases. This can be related to increasing mass transfer rate and moisture content. It has been mentioned that the swelling of the fibers and increase of WHC that occur in muscles is the reason for lower hardness (Tomac et al. 2020). Change of hardness depends on VI duration and salt concentration. Hardness increases at high salt concentrations (more than 4.5 M) due to the high extraction of the proteins. This also provides stronger protein-protein bonds that cause shrinkage of the muscle and dehydration (Shen et al. 2020). Jittinandana et al. (2002) reported that hardness increased due to an increase in myosin solubility. However, the dissolution of collagen can cause a decrease in hardness during the salting process (Jiang et al. 2019). Different marination methods affect the meat texture. Vacuum salting had higher elasticity values compared to salting under atmospheric pressure. Besides, some intrinsic factors such as protein conformation, pH, and ionic strength may affect the texture (Shen et al. 2020). Lopez Navarro (2018) reported that vacuum impregnation does not have significant impact on thickness and diameter of the products and exposes less physical deformation. Shiekh et al. (2021) showed that the texture scores of VI-treated samples were like non-VI-treated samples.

Color is an important meat quality characteristic (Ergezer et al. 2018). Color variation is related to the chemical changes in myoglobin pigment. It has been reported that brightness is related to WHC. Therefore paling occurs with increasing VI duration (Jiang et al. 2019). According to Shen et al. (2020), the redness intensity values of the VI-treated fish samples were significantly low. They explained that the denaturation of globins or low oxygen content leads to brown metmyoglobin or the conversion of bright red oxymyoglobin to purplish-red myoglobin. On the contrary, Demir et al. (2021) indicated that vacuum impregnation caused minimal changes in beef color among treatments. Perhaps species-specific effect may have caused a different effect of VI on beef than in fish.

Microbial properties. Salting is one of the oldest and most efficient preservation methods, especially for meat (Pittia and Antonello 2016). The addition of salt inhibits microbial activity by reducing a_w, and decreasing the activity of endogenous enzymes involved in improving the sensory properties of the product. It has obtained an increment in salt uptake of muscle tissue around the bone in vacuum-salted meat, which increased microbial stability (Bosse et al. 2018). Bugueño et al. (2003) evaluated some physical and chemical properties of smoked salmon processed by vacuum impregnation technique. According to their results, reducer-sulfite bacteria related to the microbial flora of smoked salmon processed by VI were not found during the storage period. Total viable and *Enterobacteriaceae* counts were below the legal limits up to 25 days of storage, and the amount of total volatile basic nitrogen (TVB-N) has been obtained below the acceptable limits of smoked salmon quality, depending on the packaging (Bugueño et al. 2003). TVB-N is a biomarker of protein and amine degradation and an indicator of microbial spoilage of meat that changes sensory acceptability (Bekhit et al. 2021).

The growth of *Enterobacteriaceae* species during the salting process of meat has a significant health risk because it contains capable pathogens and species for producing biogenic amines. Serio et al. (2017) showed that VI salting of nitrite-free lonza (B) was able to contribute to the survival of *Enterobacteriaceae*. However, *Enterobacteriaceae* were not isolated in the final product. Among the cured meat microflora, *Enterobacteriaceae* in particular, *Salmonella spp.*, *Shigella spp.* and *Escherichia coli*, and the psychrotrophic *Yersinia enterocolitica* can cause severe diarrhea. In addition, other *Enterobacteriaceae*, such as *Serratia marcescens* and *Enterobacter cloacae*, which can grow in meat products, can cause spoilage. Application of VI showed 1.0 - 1.9 log colony-forming unit/g (CFU/g) reduction on the product surface on day 1 in NB (nitrite and salt-containing brine) and B samples, respectively. The numbers of *Enterobacteriaceae* were below the limit in NB and B samples treated with conventional curing after 36 days and samples treated by VI after 60 days. These results showed that VI technique has a significant advantage in producing nitrite-free meat products.

Novel Technologies Applied with Vacuum İmpregnation

Studies have shown that the combination of several novel food technologies (e.g., ohmic heating, pulsed electric fields, electron-beam irradiation, ultrasound, CO_2-laser micro perforation, etc.) and vacuum impregnation can be effective in enhancing the quality of products by altering the structure (Yılmaz and Bilek 2018). However, some of them have been combined with vacuum impregnation in meat products based on specific requirements such as increasing mass transfer, extending shelf life, or increasing process efficiency. These technologies can be applied as pre-treatment, post-treatment, or simultaneously with VI.

Shiekh et al. (2021) used a combination of pulsed electric field (PEF) and VI to impregnate chamuang (*Garcinia cowa* Roxb.) leaf extract (CLE) (1 or 2%, w/v) in pacific white shrimp (PWS) subjected to high voltage cold atmospheric plasma (HVCAP) (Ar/ Air (80:20) atmosphere) for 10 min. They reported that the lowest melanosis scores and microbial load were found in PEF and VI treated samples, impregnated with 2% CLE and subjected to HVCAP (PEF-VI-CLE2-HVCAP) for 18 days at 4℃ compared to control and other samples. It has been mentioned that the reduction of melanosis caused higher color in PEF-VI-CLE2-HVCAP sample than in the control. These samples also had lower lipid oxidation, pH, TVB-N, and protein carbonyl content. Therefore, the shelf life of PWS has been extended to 18 days by the combination of non-thermal treatments with CLE.

VI has been coupled with ultrasound in some studies and investigated its effect on salt and water uptake in beef cubes. As a result, it has been observed that ultrasound combined with vacuum impregnation at low pressure (250 mbar) could improve diffusion and shorten the processing time by 44% (Aykın-Dinçer 2021; 2023).

The combination of VI and high hydrostatic pressure (HHP) treatments has been conducted in the marination of seabream with lemon–vinegar marinade. HHP has been used to pressurize the samples after vacuum packaging. VI combined with HHP reduced the total viable mesophilic aerobic bacteria. The drawbacks of pressurized fresh fillets were the lightness and a more "cooked" appearance, surpassing that observed in other marinated treatments (Bou et al. 2023).

VI and CO_2-laser micro perforation (Fig. 4) have been combined to accelerate mass transfer time and shown promising results. Laser micro perforation is a pre-treatment that laser creates micropores in meat samples. Ramirez et al. (2021) investigated the effect of CO_2 laser micro perforation and VI treatment on the marination time of chicken breasts.

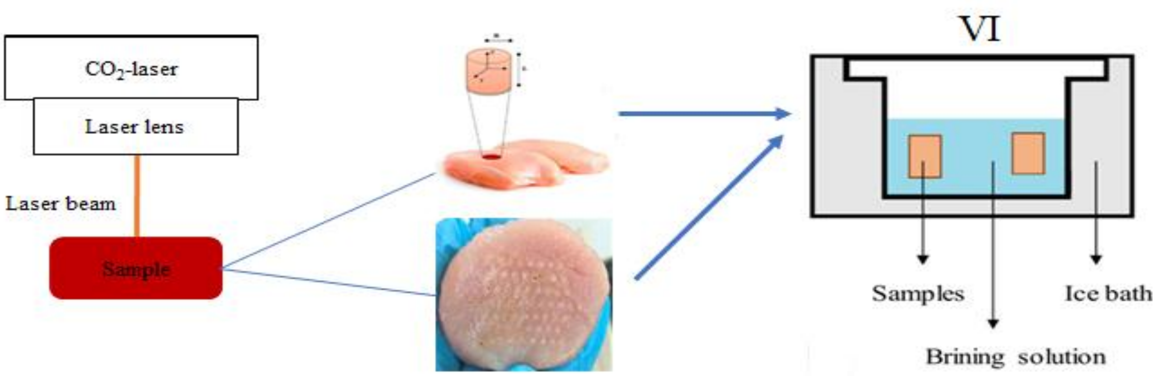

Figure 4. Combination of laser microperforation and VI (Ramírez et al. 2021)

Unmarinated chicken meat was microperforated (pores size was 228 µm diameter), then marination was applied with NaCl (3% wt/wt) and sodium tripolyphosphate (1% wt/wt) under vacuum pressure (15 kPa) at 6℃ for 60 h. According to their results combination of CO_2-laser micro perforation and VI reduced the processing time by 34% in chicken slices. Figueroa et al. (2020) applied the same combination to reduce the marination time of pork meat. Pork slices were microperforated and marinated for 60 h at 6℃ with a solution of NaCl (8% w/w) and $Na_5P_3O_{10}$ (0.3% w/w). These operations significantly accelerated the mass transfer and reduced the marination time by 47.8% compared to the traditional process.

There are limited studies evaluating the application of VI in meat and marine products, although the number of research conducted over recent years is increasing. Table 1 shows the application of VI on meat and marine products as a minimal process.

Table 1. Studies using the vacuum impregnation technique in meat and marine products

Combined use of VI with novel technologies			
Details of process	**Product**	**Results**	**Reference**
Combination of VI (Vp: 5kPa, Vt: 5 min, Rt: 5 min at 4°C) and high hydrostatic pressure (HHP) treatments (Vp: 250 MPa, Vt: 6 min at 10°C) in marination with lemon–vinegar marinade (ST: 1-2°C, SD: 16 d). HHP has been used to pressurize the samples	Seabream fillets	• VI alone had no effect on the physicochemical, oxidative stability, sensory properties, and on controlling microbial growth compared to the conventional method • The combination of VI and HHP reduced the total viable mesophilic aerobic bacteria • The color and texture have been affected by HHP	(Bou et al. 2023)
VI (Vp: 100, 250, and 500 mbar) assisted by ultrasound (180 W, 40 kHz at 4°C) in marination for 20, 40, 60, 100, 140, and 180 min with sage phenolic extracts	Meat cubes	• The highest phenolic content obtained in the UAVI-100 samples	(Aykın-Dinçer and Dinçer 2023)
Combination of pulsed electric field (PEF) and VI (Vp: 5kPa, Vt: 15 min, Rt: 15min) in marination with Chamuang leaf extract (CLE) + high voltage cold atmospheric plasma (HVCAP) (ST: 4°C, SD: 18 d). PEF has been used as pre-treatment (frequency: 10 Hz, pulse interval: 10 ms, and pulse duration: 100 ms)	Pacific white shrimp	• Samples treated with 2% CLE by PEF and VI subjected to HVCAP had the lowest microbial load during 18 d. It also had lower lipid oxidation, pH, total volatile base (TVB), and carbonyl content • Shelf life was extended by using non-thermal processes.	(Shiekh et al. 2021)
Combination of ultrasound (US) and VI (Vp: 250, 500, and 750 mbar, Vt: 10min, Rt: 10min) pretreatments in beef marinated with onion juice (ST: 4°C, SD: 24 h). Ultrasonication (frequency: 40 kHz) has been simultaneously used with VI	Beef	• The shortest salting time obtained in US-VI 250 samples	(Aykın-Dinçer 2021)
Use of pulsed vacuum (Vp: 15 kPa, Vt: 150s, Rt: 4s) and laser micro perforations in marination of chicken meat (ST: 6°C, SD: 60 h). Laser micro perforation has been used as pre-treatment (35% of the total 100-W power, 300 pulses with a 2 µs duration and a delay of 1 µs between pulses)	Chicken meat	• Solution uptake was promoted by VI and micro perforation (either individually or in combination however, the best results were obtained in the combination of VI+ micro perforation), and process time was reduced by 34%.	(Ramírez et al. 2021)

Marination of pork meat by the combination of vacuum impregnation (Vp: 6.67 KPa, Vt: 5 min, Rt: 2 min) and CO_2-laser micro perforations (ST: 8°C, SD: 60 h). Laser micro perforation has been used as pre-treatment (45 W, 300 pulses with a duration of 1 s)	Pork meat	• Compared to traditional marination, the mass transfer was significantly accelerated, and the marination time was reduced by 47.8%.	(Wang et al. 2020)

Vacuum impregnation (only used)

Details of process	Product	Results	Reference
Utilization of vacuum impregnation (Vp: 10 kPa, Vt: 5 min, Rt: 5 s) combined with water-soluble polyphenol extracts (pomegranate peel (PPE), grape seed (GSE), and green tea (GTE) in the coating of fish (ST: 4℃, SD: 12 d)	Grass carp slices	• Low TBARS, TVB-N, and K value in coated groups compared to control • The lowest TVB-N, TBARS, K value, water loss, and the highest shear force and sensory preference values belonged to chitosan-green tea extract.	(Zhao et al. 2021)
Utilization of ultrasonication (US) (frequency: 37 kHz, working power: 150W) and VI (Vp: 0.1 MPa, Vt: 20, 40, 60 min) pretreatments (individually) in beef marination with onion juice (ST: 4°C, SD: 24 h)	Beef	• US and VI pretreatments improved marination uptake • Low levels of tyramine, spermine, and putrescine • No adverse effects on sensory properties.	(Demir et al. 2021)
The effect of various salt concentrations and time under vacuum impregnation (Vp: 70 kPa) (ST: 4°C), the ratio of fish to solutions was 1:3 (w/w)	Russian sturgeon (*Acipenser guelden-staedtii*)	• Vacuum impregnation increased salting efficiency and WHC • Preserved microstructure, especially after 2 h of salting, Increased hardness and springiness values, decreased L^* and a^* values • Additionally, vacuum-impregnated fillets had lower TVB-N and carbonyl content after 5 h of salting.	(Shen et al. 2020)
Effect of Vacuum impregnation (Vp: 10000 Pa, Vt: 5 min, Rt: 420 min) on mass transfer kinetics, texture, and color (ST: 4°C), (1:10 fish to solution ratio)	Hake fillets *(Merluccius hubbsi)*	• VI treatment did not affect color and texture compared to the control • Reduced processing time and increased absorption.	(Tomac et al. 2020)
Coating by vacuum impregnation (Vp: 5 kPa, Vt:15 min, at: 10 min) with fish gelatin (FG) and grape (GSE) seed extract (ST: 4°C, SD: 12 d), the ratio of the fillet to coating solution was 1:3	Tilapia fillet	• Reduction of drip loss, texture changes, and microbial survival • Delayed protein oxidation by inhibiting the formation of disulfide bonds and carbonyl groups and maintaining higher sulfhydryl content and Ca^{2+}-ATPase activity • Overall, VI-treated coating included 3% FG+0.9% GSE showed the best preservative effect on fish fillet quality and extended shelf life.	(Zhao et al. 2019)

Vacuum impregnation (Vp: 0.06 MPa) with herring anti-freezing protein (AFP) combined with CS@Fe_3O_4 nanoparticles during freeze-thaw cycles (stored at −20℃ for 24 h, followed by thawing at 4℃ for 12 h)	Red sea bream (*Pagrosomus major*)	• VI inhibited ice crystal growth and reduced ice crystal sharpness to improve the quality of the final product • Minimized freeze-thaw damage • Prevented lipid and protein oxidation • Reduction in the cost of frozen foods.	(Nian et al. 2019)
Application of pulsed-vacuum (Vp: 10 kPa, Vt: 5 min) on the salt uptake, the ratio of sample/solution was 1:20 (w/v)	Pirarucu (*Arapaima gigas*) fillet	• Increment in salt uptake • Efficient salting process at room temperature or under refrigeration.	(Martins et al. 2019)
Use of VI (Vp: 0,1 MPa, Vt: 20, 40, and 60 min) for marination with onion juice	Beef	• More tenderness of meat compared to traditional marination • Reduction of lipid oxidation.	(Çelik 2019)
Effect of vacuum impregnation (Vp: 20.3 or 71.1 kPa, Vt: 0.5, 2.0 or 4.0 h) on meat quality, the ratio of meat to the solution was 1:5 (w/w)	Cull cow meat	• Similar weight gain compared to traditional injected meat; however, lower sodium levels and more homogeneous distribution of brine into meat, high amount of intra-myofibrillar water, and more tenderness and juiciness after cooking • A good alternative in the production of moisture-enhanced meat products.	(Leal-Ramos et al. 2018)
Salting by vacuum brine impregnation (Vt: 20 min) in nitrite-free lonza: effect on Enterobacteriaceae, the ratio of meat to the solution was 1:2 kg.kg^{-1}	Lonza (pork meat)	• Contrary to the traditional brining process, VI reduced the *Enterobacteriaceae* population on the product surface but induced contamination of the inner muscle tissues.	(Serio et al. 2017)
Effect of vacuum impregnation (Vp: 6.67 kPa, Vt: 20min) on acid addition and partial replacement of NaCl by KCl during salting (ST: 10 °C, SD: 6 h)	Beef cuts	• Less salting time • Application of VI, increased water loss (20%) and salt uptake (15%) compared to atmospheric pressure • The addition of different acids to brine reduced salt uptake by 13-24%. • The higher diffusion rate of K^+ than Na^+.	(Bampi et al. 2016)
Influence of pulse vacuum brining (Vp: −70 kPa, Vt: 15 min, at: 15 min) on microstructural, protein denaturation, and water holding properties (SD: 6 h)	Lamb	• Higher salt content (1%), greater STK before 4.5 h and more dissolved actomyosin in VI-treated samples • More swelling properties of myofibrils and larger myofibrils diameters • VI increased brine efficiency and reduced time.	(Wang et al. 2016)
Use of immersion and vacuum impregnation (Vp: 50 mbar, Vt: 15 min, Rt: 0, 15, 30, 45, 75, and 105 min) in marinated Salmon production	Salmon (*Salmo salar*)	• High salt and sugar uptake (significant increase in salt content due to the higher solubility of salt at 5℃ compared to sugar) • More efficiency in a short time.	(Larrazábal- Fuentes et al. 2009)

Effect of storage conditions on smoked salmon processed by vacuum impregnation technique (Vp: 50 mbar, Vt: 5 min, Rt: 45 min) (ST: 2℃, SD: 30 d)	Salmon fillet (*Salmo salar*)	• The shelf life of both vacuum and MAP packaging was limited to 25 d by microbial growth • TVB-N and TBARS were found below the acceptable limits during storage • Harder and less watery product in vacuum packages.	(Bugueño et al. 2003)
Brining of turkey meat by VI and impact of vacuum cycles on mass transfer (Vp: 20 kPa, Vp: 300 s, Rt: 300 s)	Turkey breast	• More salt content and low dehydration than traditionally brined products, high mass yield • Homogeneous salt and water distribution • The number of vacuum cycles, long vacuum phases, and shorter atmospheric pressure duration led to increased mass transfer.	(Deumier et al. 2003)

Vp – vacuum pressure; Vt – vacuum time; Rt – restoration time; ST – storage temperature; SD – storage duration; $L*$ – lightness; $a*$ – redness; K value – freshness indicator of meat; At – atmospheric pressure time.

To summarize Table 1, VI has excellent potential for improving the overall quality and increasing the shelf life of meat and marine products. It has been reported that VI provides advantages in increasing mass transfer rate, external solution uptake, WHC, and sensory and technological quality parameters in various meat and marine products. VI-treated meat products could successfully enhance processing yield and protected texture and sensory parameters (Demir et al. 2021). VI was adequate to prevent oxidation and microbial growth, and it could decrease TVB-N and biogenic amines (Shiekh et al. 2021).

Conclusion

It is clearly understood that more studies should be done on using VI in meat since there are many effective parameters in the vacuum impregnation process, and the final product properties are also affected by these parameters. VI technique has the potential to use with different technologies such as ultrasound, laser micro perforation, etc. Vacuum impregnation was most used in marination, brining, and salting; however, there are limited studies in other processes e.g., modification of formulation, pretreatment of drying, coating, etc. It is thought that increasing the studies in this field can bring different features to the product. Since there are few studies on the oxidation of VI-treated samples, there are different approaches, so more information is required.

Acknowledgments

The authors are thankful to Ege University Scientific Research Projects Coordination under project number 23867 for their financial support.

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