

REVIEW PAPER

Vacuum Impregnation: Applications in Food Industry

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ABSTRACT

Vacuum impregnation (VI) is an improved osmotic dehydration technology emerging in food industry for the development of high quality and nutritionally rich food products. The VI technology helps to rapidly impregnate animal or plant tissue pore spaces with required external solution producing a product with improved qualities and better shelf-life with minimal changes in nutritional and sensory properties. This paper provides a general review of the principles, mechanisms of VI technology and different external and internal factors affecting the treatment on foods. Different applications of VI such as calorie densification, food salting, fortification, pre drying and freezing etc. are also discussed. The VI has considerable potential to be employed in the food industry. Yet, technological problems like precise control and maintenance of process conditions need to be solved in order to achieve better impregnation and treatment homogeneity.

Keywords: Vacuum impregnation, food quality, osmotic dehydration, functional foods, caloric densification, mesoscopic divided material

Increased consumer preferences in high quality and nutritionally rich food have led to significant development of different technologies in food industries. As a part of this revolution, foods with added health benefits and quality have occupied a larger market as functional foods and fortified foods. In the present scenario, different technologies are developed to provide bioactive compounds to food materials without affecting the structure and quality. Vacuum impregnation (VI) is one of such recent technologies developed to fulfil the needs of consumers.

Vacuum impregnation is a developed version of osmotic treatment technology, in which moist air and a part or whole of the intact solution are removed from food pore space and substituted by the desired solution (Fito *et al.* 1994). The process happens in two stages in which the first stage is the application of vacuum pressure to the product for removing solution and gases and the second stage is to impregnate the

product with a desired solution with regaining the atmospheric pressure.

Vacuum impregnation is a non-thermal technology and has wide application in food processing. The technique can be well utilised for the production of functional and fortified food products. The physiologically active compounds can be deliberately added to the structure of food product. Similarly, fortification of food with required nutraceutical compounds can be done without affecting the structure of food.

FOOD MATERIAL STRUCTURE

Food structure can be categorised in different spatial scale such as macroscale mesoscale and microscale. The macroscale considers food as a whole or a group of biological tissues having uniform characteristics. Mesoscale represents to the topology of biological tissues. The microscale refers to the variations in individual cells as cell membranes, cell walls and

internal organelles, etc. VI technology imparts importance to the evaluation of food at mesoscopic scale which considers them as mesoscopic divided material (MDM). The mesoscopic scale studies three-dimensional architecture of foods by analysing the relation among solid phase and void phase, where the capillaries or pores may be moderately or entirely filled with gases or liquids. The sensorial and/or nutritional qualities of foods are highly influenced by the relations between solid and void phases and their variations during processing. Vacuum impregnation is one of the important and newest technologies which depend on the characteristics of food microstructure. With this term some techniques are categorised based on the utilisation of pore fraction of foods with the aim to impregnate the organic/chemical compounds into the pores of biological tissues in a controlled way (Derossi *et al.* 2012).

MECHANISM OF VACUUM IMPREGNATION

During vacuum impregnation process the infusion of external solution to the capillaries and free spaces of the biological tissue are due to a mechanically developed pressure difference. VI consists of two stages which include stage of vacuum pressure and stage of atmospheric pressure. Infusion of the solution occurs as a result of two processes such as hydrodynamic mechanism (HDM) and deformation–relaxation phenomena (DRP), which lead to the filling of intracellular spaces (Fig. 1). Initially immersion of the material in solution (t_0), the pressure inside (p_i) and outside (p_e) the capillary are equal to atmospheric pressure ($p_i = p_e = p_{at}$) and they equalize. The initial volume of the capillary (V_{g0}) is filled with gas (Fig. 1, Step 0). In the first phase of the process, the pressure is reduced ($p_1 < p_{at}$). As a result of the difference in pressures, the gas is removed from the capillary. Reduced pressure acting from the outside causes the deformation and expansion of the capillary, which is the first part of the deformation–relaxation phenomenon (DRP). The volume of the capillary is increased ($V_{g1A} = V_{g0} + X_{c1}$). This stage lasts until pressure equilibrium ($p_i = p_e$) is reached (Fig. 1, Step 1A). Next, the capillary starts to be

partially filled with solution, as a result of the HDM. The pressure inside the capillary increases slightly, while the free volume inside it decreased to the value $V_{g1B} = V_{g0} + X_{c1} - X_{v1}$ (Fig. 1, Step 1B). In the second phase of vacuum impregnation the pressure returns to the atmospheric value. This causes the transition of the DRP to the relaxation phase. The capillary shrinks to an even greater extent than before the start of the process. At the same time, as a result of the action of capillary pressure and decompression, an intensive inflow of liquid from the outside to the inside of the capillary is observed and the final volume of gas inside it decreases to $V_{g2} = V_{g0} - X_c - X_v$ (Fig. 1, Step 2). The relaxation phase is particularly important from the practical point of view, since tissue impregnation occurs at this stage. Removal of vacuum should not be too rapid, since the excessively fast pressure equalization may lead to closure of the capillary vessels and inhibition of the hydrodynamic mechanism (Fito *et al.* 1996; Salvatori *et al.* 1998).

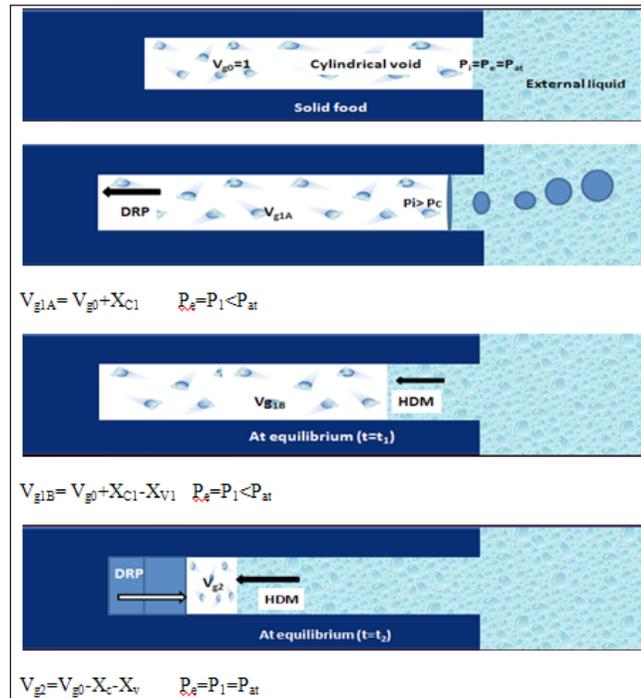


Fig. 1: The hydrodynamic mechanism (HDM) and deformation-relaxation phenomena (DRP) contribute to the filling of the ideal capillary with liquid during vacuum impregnation. (t -Time; t' -Time required

for internal and external pressure become equal; t_1 -Time of vacuum applied (vacuum time); t_2 -Time of atmospheric pressure (relaxation time); p_0 -Initial pressure; p_1 -Vacuum pressure; p_2 -Final pressure; p_i -Internal pressure; p_e -External pressure; p_c -Capillary pressure; p_{at} -Atmospheric pressure; V_{g0} -Initial volume of gas trapped into the capillary; V_{g1A} , V_{g1B} , V_{g2} -Volume of gas trapped into the capillary after each step of vacuum impregnation; X_{c1} -Increment of volume of gas trapped into the capillary as result of DRP; X_c -Decrement of volume of gas trapped into the capillary as result of DRP; X_{v1} -Partial decrement of volume of gas trapped into the capillary as result of HDM; X_v -Decrement of volume of gas trapped into the capillary as result of HDM).

MODELLING OF VACUUM IMPREGNATION

Mathematical modelling of the phenomenon during VI was first studied by Fito (1994) and Fito *et al.* (1996). The modelling was based on the processes occurring at macroscopic scale during VI. The analysis of contributions of liquid penetration and solid matrix deformation of an ideal pore volume ($v_{g0}=1$) during each step of VI is expressed as:

$$V_{g1b} = 1 + X_{c1} - X_{v1} \quad \dots(1)$$

Where V_{g1b} is the pore volume at the step 1-B, X_{c1} is the increment of pore volume due to the expansion of internal gases and X_{v1} is the partial reduction of pore volume due to the initial suction of external liquid as a consequence of HDM.

At the end of step 2, the total liquid penetration and matrix deformation may be described respectively by the equations:

$$X_v = X_{v1} + X_{v2} \quad \dots(2)$$

$$X_c = X_{c1} - X_{c2} \quad \dots(3)$$

where X_{v1} and X_{v2} are the volume reduction due to liquid penetration respectively at the end of step 1 and 2; X_{c1} and X_{c2} are the volume pore changes as a result of solid matrix deformation (enlargement and compression) after the steps 1 and 2. Also, the total

volume variation at the end of the process may be described as given below:

$$V_{g2} = 1 + X_c - X_v \quad \dots(4)$$

Equations 2 and 3 may be used to calculate liquid penetration and solid matrix deformation of the total sample taking into account its porosity fraction value (ϵ_e):

$$X = \epsilon_e X_v \quad \dots(5)$$

$$g = \epsilon_e X_c \quad \dots(6)$$

As reported from Fito *et al.* (1996) when a pressure variation applied in a solid-liquid system and an equilibrium situation is reached, HDM assumes an isothermal compression of gas into the pores. So, the situation reached at the end of step 1-B may be mathematically expressed as:

$$\frac{V_{g1B}}{V_{g1A}} = \frac{1 + X_c - X_v}{1 + X_c} = \frac{1}{r} \quad \dots(7)$$

Where r is the apparent compression rate ($r \sim$ atmospheric pressure/vacuum pressure) (Zhao and Xie, 2004). From equation 7, the following may be obtained:

$$\frac{X_{v1}}{1 + X_{c1}} = 1 - \frac{1}{r} \quad \dots(8)$$

Also, by using the equation 5 and 6 it is possible to obtain

$$X_1 = (\epsilon_e + \gamma) \left[1 - \frac{1}{r_1} \right] \quad \dots(9)$$

On the basis of these, the equilibrium situation at the end of step 1-B may be mathematically expressed as:

$$X_1 - \gamma_1 = \epsilon_e \left[1 - \frac{1}{r_1} \right] - \frac{\gamma_1}{r_1} \quad \dots(10)$$

Furthermore, the same considerations may be extended for the phenomena involved from step 1

and step 2. So, between $t = t_1$ and $t = t_2$ the equilibrium situation may be expressed as:

$$X_1 - \gamma = (\varepsilon_e + \gamma) \left[1 - \frac{1}{r_1} \right] - \gamma_1 \quad \dots(11)$$

Starting from the above equations it is possible to calculate the porosity value (ε_e) at the end of VI process from the value of X , and by:

$$\varepsilon_e = \frac{(x - y) r_2 + \gamma_1}{r_2 - 1} \quad \dots(12)$$

Where X is the volume fraction of sample impregnation by the external liquid at the end of VI treatments (m^3 of liquid/ m^3 of sample at $t=0$), ε_e is the effective porosity, γ_1 is the relative volume deformation at the end of vacuum period (t_1 , m^3 of sample deformation/ m^3 of sample at $t=0$); γ is the volume deformation at the end of process (m^3 of sample deformation/ m^3 of sample at $t=0$).

VACUUM IMPREGNATION SYSTEM

The VI system consists of a VI chamber, pressure control valves, a vacuum pump and a pressure sensor which is connected to a data acquisition system and a circulation path for the solution. The VI chamber contains the impregnating solution with sample immersed in it and the temperature is maintained using a thermostatic bath.

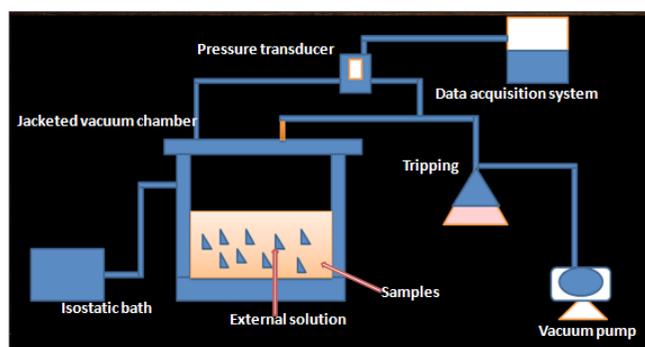


Fig. 2: Vacuum impregnation experimental device

A vacuum pump is connected to the chamber to reduce the pressure for a short time and an external solution is circulated to the tank using a centrifugal pump.

The vacuum pump is connected to a proportional solenoid valve coupled to a pressure transducer and to dedicated software that performed valve control and data acquisition (Lima *et al.* 2016).

Process variables

The process of vacuum impregnation includes the application of a vacuum pressure (P) to the headspace of food for time (t_1) and after restoration of atmospheric pressure for a relaxation time t_2 . The VI process depends on different factors, which includes internal and external factors of foods. The internal variables are related to the inherent structure of food materials and include the mechanical properties and three-dimensional structures of food materials. The external variables comprises time length of vacuum period (t_1), vacuum pressure (P) the time length of relaxation period (t_2), temperature, the viscosity of the external solution, concentration of the solution, solution/product ratio etc.

External variables

Vacuum pressure (P)

Vacuum pressure is one among the external variables of VI process. It is the pressure required to produce force to develop pressure gradient between the pore phase of food and the surrounding atmosphere of the external liquid. Generally, VI process operated in a vacuum pressure varies between 50 and 600 mbar (Fito *et al.* 1996; Rastogi *et al.* 1996; Salvatori *et al.* 1998) vacuum pressure is usually recognised as directly associated to a raise of impregnation level (X) as a result of an intense removal of indigenous gases and liquids united with a greater DRP and HDM.

Mujica-Paz *et al.* (2003) evaluated the effect of vacuum pressure in a range of 135-674 mbar on the volume of voids impregnated from an isotonic solution of different fruits. It was observed that a higher impregnation level proportional with an increase of vacuum pressure for papaya, apple, melon and peach samples. Derossi *et al.* (2010) studied the application of vacuum impregnation for acidification of pepper slices, which showed that a lower pH ratio values

(RpH) were obtained for pressure of 200 mbar while compared to a pressure of 400 mbar.

Phianmongkhol and Wirjantoro (2016) reported that sucrose solution was extensively incorporated into samples of unripe mango processed at 50 mbar vacuum pressure than those of samples of ripen treated at atmospheric pressure. The effects of vacuum pressure implies that there was a greater release of native liquid and gases occurred at higher vacuum pressure up to 50 mbar (Derossi *et al.* 2012). With natural colorant enrichment of apple tissue with black carrot concentrate using vacuum impregnation, the a^* value of apple samples increased when the pressure and time increased to some extent (Yılmaz and Bilek 2017).

Yang (2017) investigated on impregnation of papaya cubes with Pectin methylesterase and calcium lactate. It was observed that higher vacuum pressure was found better at retaining hardness with time of storage in papaya slices. Also, the hardness of papaya slices processed under 5 kPa was extensively harder than untreated.

Vacuum period and relaxation time

During vacuum impregnation process period of vacuum application and relaxation times considered as two vital factors affecting the rate of impregnation. Vacuum period (t_1) represents the time of vacuum application for food microstructure required to reach an equilibrium situation. As mentioned before, different processes such as deformation (expansion) of capillary pores, the removal of inherent liquids and gases from the voids and the partial impregnation of voids concurrently happen for the period of t_1 . Whereas, relaxation time (t_2) is the period during which food structure moves towards an equilibrium situation after the restoration of atmospheric pressure. At the period of t_2 , impregnation of capillaries (by HDM) and deformation (compression) of voids happen due to the action of a negative pressure gradient. Generally, the time length of both vacuum time and restoration time affects on the increase in impregnation level of foods (Derossi *et al.* 2012).

Hironaka *et al.* (2011) studied about the fortification of the potato with ascorbic acid using vacuum impregnation process and observed that a raise of vacuum time from 0 to 60 minutes was capable of improving the ascorbic acid content in whole potatoes of different varieties. Derossi *et al.* (2010) obtained positive effect of vacuum time on considerable pH reduction of pepper slices treated with VI at 200 mbar pressure.

Considering the effect of vacuum time on vegetables and fruits during VI treatment, Gras *et al.* (2003) applied a vacuum pressure of 50 mbar and a vacuum period of 10 min for calcium impregnation of carrots and eggplants. Guillemin *et al.* (2008) carried out VI treatment at vacuum pressure of 0.05 bar for 2 min in apple cubes using sodium chloride and/or sodium alginate to improve the firmness. But, in the case of whole potatoes a long vacuum time was needed for impregnation of external solution in to thick periderm of whole potatoes, which are fewer permeable to gas and water (Peterson *et al.* 1985).

EXTERNAL SOLUTION

Selection of external solution

The vacuum impregnation solution is selected on the basis of the purpose and type of final product required. Selection of the external solution is one of the important steps in VI process. The osmotic solutions are generally three types such as isotonic, hypotonic and hypertonic. The isotonic solution containing equal solute potential both inside and outside of the cell membrane, product placed in such solution, cells neither shrink nor swell. Hypotonic solution has low solute concentration outside the cell membrane than inside; the product placed in such solution will swell due to water movement towards high solute concentration. In hypertonic solution higher will be the solute concentration outside the cell membrane than inside. Products placed in such solution will shrink due to water removal from the cell towards the solution which leads to partial dehydration.

The identification of suitable VI solution should also consider solubility of solute in solution. Usually, low

molecular carbohydrates are utilised for vacuum impregnation since low molecular carbohydrates can easily penetrate to cells than high molecular compound such as glucose (Garrote and Bertone, 1989).

Solution characteristics

The important aspect of impregnating solution includes temperature, concentration, agitation and solution to product ratio. These properties have a significant effect on the vacuum impregnation process. Different studies found that high concentration of external solution leads to high rate of mass transfer. The increase in solution concentration to 50-60% resulted in reduction in mass transfer or stabilization of the process (Yang and Maguer, 1992). The effects of solution concentration of glycerol, glucose, and sucrose on halved strawberries were studied by Garrote and Bertone (1989). They observed that the increase in solution concentration along with increased solution viscosity led to a reduction in solute transfer rate, which negated out for the raise in the difference in concentration.

Temperature is another one factor of external solution which has direct affects on the mass transfer in different treatments such as acidification, brining, osmotic dehydration, etc. Temperature also has significant affects on the visco-elastic characteristics of solid food matrix and viscosity of the exterior solution.

Different authors have reported that increase in viscosity of solution led to decreased diffusion of solutes into fruits and vegetable tissues (M'ujica-Paz *et al.* 2003; Guillemin *et al.* 2008). Guillemin *et al.* (2008) found that when a 2% sodium alginate solution was used solute allocation was heterogeneous and confined to the surface. High viscous solutions require longer restoration time after vacuum period. This is because more time needed to achieve a better impregnation level, uniform diffusion and better distribution of solutes.

The ratio of VI solution to product is an important parameter. The optimum value is usually determined

by two factors: stability of the solution during processing, and the economics of transport and recycling of the solution. A high solution to sample ratio ensures retention of a constant solution concentration during processing. However, the high ratio increases cost and necessitate solution recycling. Lenart and Flink (1984) suggested that a value of 4-6 might be optimal for the best osmotic effect.

Internal variables

Vacuum impregnation process depends on the properties of food components at both microscopic and mesoscopic scale (Fito *et al.* 1996; Salvatori *et al.* 1998). The porosity fraction of biological tissue is considered as one of the important parameters for the VI treatment because it represents the void space potentially available for the influx of the external solution. Generally, fruits and vegetables are considered as highly suitable for vacuum impregnation process due to its greater porosity fraction compared to other products such as fishes, meats and cheeses.

Generally, increase in porosity fraction increases the impregnation level in biological tissues. The vacuum impregnation of several biological materials with different porosity fraction was studied by Fito *et al.* (1996) and concluded that the impregnation level of banana, mushroom, apple, strawberry and apricot samples was proportional to their effective porosity values. VI treatments of carrots, oyster mushroom and eggplants for the fortification of calcium were studied by Gras *et al.* (2003). They observed highest level of impregnation (X) values for oyster mushrooms and eggplants which showed a greater intercellular porosity of 41%±2 and 54%±1 respectively in comparison with carrots.

As reported from Zhao and Xie (2004), during VI three main phenomena are involved: gas outflows, deformation-relaxation of solid matrix and the liquid influx. Since these phenomena simultaneously occur, the result of VI is a consequence of the equilibrium among their kinetics which, in turn, is affected by (Fito *et al.* 1996):

- ❑ Structure of tissue (distribution of size and voids).
- ❑ Relaxation time of the solid matrix, a function of the viscoelastic properties of the material.
- ❑ The rate of HDM, a function of porosity, size and shape of capillaries, their connectivity, the viscosity of solution.
- ❑ Shape and size of products.

APPLICATIONS OF VI TECHNOLOGY

Calorie densification

Food materials are composed of large quantities of water and air spaces and these constituents are found to be effective in providing calorie values to the food and occupy a large volume. The elimination of these calorieless constituents and replacing or filling the water and void space with nutrients is a direct method of calorie densification. The calorie densification is a process to increase the calories available per unit volume. The caloric density of product is affected by both physical and chemical factors.

The caloric densification is mechanically accomplished by direct compression of energy-rich products and infusion of water pores and voids spaces of the product with energy-rich constituents and dehydration of products by removing water with zero calories. Vacuum impregnation method is one of the calorie densification processes in which calorie-less constituents such as water and air are partially removed and the voids are filled with calorie-rich external solution without affecting the structure. Different calorie rich filling materials used in VI process includes large parts of melted fat or carbohydrates such as sucrose solution (Kumar *et al.*, 2015).

Reduction of pH

Usually, food materials are acidified by the method of blanching and soaking which is more time consuming and also causes loss of some soluble bio-active compounds from product. The vacuum impregnation technology can be a better method

for pH reduction due to the short processing time and quality retention. Several studies have reported that vacuum impregnation treatment successfully reduced the pH of the food materials (Radziejewska-kubzdela and Kido, 2014).

Dessoi *et al.* (2010) reported that VI improves the rate of pH reduction in vegetables and it was found to be lesser than conventional methods. During the VI process, the capillaries are filled with external solution, which increases the surface contact area than conventional method. Hence the rate of diffusion of the hydrogen ions from solution to vegetable tissue also increases. The pH reduction process depends upon several factors such as the vacuum pressure, porosity of vegetable tissue, mechanical properties etc.

Pepper slices treated at 400 and 200 mbar and 30 min relaxation period observed a 0.929 to 0.894 reduction in pH ratio whereas the pepper slices treated with conventional method showed a pH ratio of 0.968. The vacuum pressure was found to be most important parameter effecting the reduction of pH (Dessori *et al.* 2010).

Pre-freezing method

Vacuum impregnation as a pre-treatment for freezing has been studied to advance the quality of frozen fruits and vegetables by improving texture quality and reducing drip loss with energy economy at the time of freezing (Torreggiani and Bertolo, 2001; Xie and Zhao, 2003b).

Vacuum impregnating with cryoprotectants which are generally cryostabilizers or hypertonic sugar solution have been recommended for reducing freezable water content and decreasing the injury due to ice crystals in frozen materials (Levine and Slade, 1990; Martinez-Monzo *et al.* 1998). VI treatment with hyper tonic solution leads to osmotic dehydration due to collective effort of capillary action and pressure difference (Fito & Pastor, 1994). Vacuum impregnation of apple before freezing used concentrated grape must and pectin solution as cryopreservative (Martinez-Monzo *et al.* 1998).

Grape must impregnated apple showed improved mechanical properties due to reduction in amount of freezable water whereas VI with pectin showed better stability of frozen product by increasing the glass transition temperature of liquid phase and also formation of intercellular 'bridge' from polysaccharide gels that strengthened the arrangement of cellular matrix. VI with cryoprotectants and calcium have enhanced the texture and reduced drip loss of frozen-thawed berries. The drip loss was reduced up to 20-50% while comparing with untreated at increased compression force of about 50-100% (Xie and Zhao 2003).

Food salting

A salting VI technology has been proposed (Chiralt and Fito, 1997) to considerably reduce salting time. Pressure gradient created during VI treatment increased the salt uptake by hydrodynamic mechanisms (HDM) taking place in capillary pores (Gonzalez *et al.* 1999). VI application in salting processes of spongy foods increases the solute yield with faster salting kinetics and uniform distribution of salt in the material (Chiralt *et al.* 2000).

Brine vacuum impregnation has been found to decrease time of salting in ham for curing (Barat, Guru 1998) and manchego type cheeses (Chiralt and Fito 1997), while providing a uniform salt allocation in the food. The combination of hydrodynamic mechanisms with the diffusional phenomena promoted by concentration gradients hastened the salt uptake (Fito 1994).

Pre-treatment of drying

The vacuum impregnation treatment has been introduced as a pre-treatment before drying to obtain goals such as saving of energy along with incorporation of functional compounds or anti browning or anti microbial compounds to food material for quality improvement.

During pre-drying treatment of fruits and vegetables using VI process, at first stage, the gas capillaries of materials can escape from the interior of products.

In the second stage the container restores the atmospheric pressure thus reduces internal gas volume in the material which sharply reduces with the increase in pressure. Plant tissue takes some time to contract because of its visco-elastic property. Then the liquid material outside the product will flow to the porous capillary (Fito *et al.* 2001).

The combination of final air drying and VI pre-treatment resulted in a product with lower water activity and softer food compared to the normal drying process (Maltini *et al.* 1993). The VI pre-treatment provides a better preservation of pigments with narrowed moisture diffusivity of samples (Alvarez *et al.* 1995; Tongini and Betoto 2001). Impregnation of apple samples with glucose strongly reduced the moisture transfer and volume shrinkage during drying.

Functional products

Probiotics are living bacteria of selected strains, which provide a beneficial outcome on human wellbeing following consumption. Most of the probiotics foods available in markets are dairy produce, which have basically two disadvantages such as high cholesterol content and lactose intolerance. Attempts to apply vacuum impregnation for the incorporation of probiotics to the matrix of fruit and vegetables will help to extend the range of probiotic food produce (Granato *et al.* 2010; Pere *et al.* 2012).

In vacuum impregnation process higher quantity of impregnating solution is infused into the plant tissue (Diamante *et al.* 2014) due to hydrodynamic mechanism developed under pressure gradient; accordingly, a greater number of probiotic cells may be incorporated into the fruit. Several researchers have demonstrated that VI effectively incorporates nutrients (e.g. bioactive compounds and probiotic microorganisms) into fruits and vegetables (Comandini *et al.* 2010; Betoret *et al.* 2012; Andrade *et al.* 2017).

Vacuum impregnated probiotic-enriched dried samples of apple contained about 10^7 CFU/g of microorganisms. Probiotic rich apple snacks were

formed by impregnating apple cylinders either with apple juice containing *S. cerevisiae* or with whole milk containing 10^7 – 10^8 CFU/ml of *Lactobacillus casei* (*spp. rhamnosus*) (Betoret *et al.* 2003).

Thermal properties

The thermal properties of fruit and vegetables can be modified using Vacuum impregnation. The composition and structure of raw material determine the conductivity and thermal diffusion coefficient of product. Modifying the structure of material through VI before the thermal processing may enhance the heat conduction efficiency and improve the product quality. Martínez-Monzó *et al.* (2000) observed an increase in thermal conductivity by 15%–24% in apples vacuum impregnated with an isotonic sucrose solution, while slight variation in the diffusion coefficient were monitored. Fito *et al.* (2000) found that increase in thermal conductivity may be due to the replacement of gas in intracellular spaces with the solution, while an increase in density may cause minor increase in the diffusion coefficient.

Fortified products

Vacuum impregnation has been used as a method to incorporate desirable components into the spongy structure of foods, suitably improve their unique constitution as a technique for new products development (Fito, 1994; Fito *et al.* 1996; Martínez-Monzo *et al.* 2000; Chiralt *et al.* 2001). The possibility of application of VI for fruits and vegetables fortification with minerals was first studied with an engineering point of view by Fito *et al.* (2001). They developed different mathematical models for determining required amount of various minerals in the solution of VI to obtain around 20–25% dietary reference intake (DRI) in 200 g of samples. From the predictions of modelling, experimental confirmation established that VI could be used as a successful way for fruits and vegetables fortification with vitamins, minerals or other bioactive compounds.

Oyster mushroom, eggplants and carrots fortified with calcium using VI showed that changes in raw

material induce sharp variations in the ultimate impregnation level; greatest impregnation levels were reported in mushrooms and eggplants due to their high intercellular porosity and are thus much fitting for fortification of products. The calcium distribution in plant tissues was studied using microanalysis, which indicates that mushroom and eggplant showed calcium in the intercellular spaces while xylem in carrots (Gras *et al.* 2003).

RESEARCH GAPS

Vacuum impregnation was introduced at least 20 years ago; however it is still considered an emerging technology with enormous applications. The most important future challenge of the technology will be the precise characterization of the three-dimensional architecture of foods, its transformations during food processing and its relation with quality and safety (Datta, 2007). Also, the lack of information for industries on the advantages of these techniques may be a reason for its reduced applicability at industrial level.

Another lacuna entails the shortage of industrial plants in which it could have been possible to have accurate control of the operational parameters during the two steps of the process. The absolute immersion of foods into the surrounding solution is a challenge for the proper application of VI as low-density fruits and vegetables are likely to float with outside solution (Zhao and Xie 2004). Hence, VI is applied by continuously stirring solution with the goal of keeping food pieces submerged in solution, causes increase in power consumption and possible damages of foods.

CONCLUSION

Vacuum impregnation process has been used as methods to impregnate food with nutritional and functional compounds, to introduce some ingredients with the aim to attain food with innovative sensorial properties in addition to incorporating compounds which are able to restrict the degradation reactions and the microbial growth. VI has shown to be very

useful in wide number of industrial applications. Furthermore, from an engineering point of view VI has various advantages such as fast process, low energy costs, could be performed at room temperature, and possibility to reuse the external solution. Even though VI was for first time proposed years ago, it has been still considered as an emerging technology with high potential applications because industrial scale application is yet very poor. Thus, the present researches aims to throw light on the importance of VI in food processing and how it improve the quality of food products.

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