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Review article

Recent advances in vacuum impregnation of fruits and vegetables processing: A concise review

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ABSTRACT

Vacuum impregnation (VI) is a novel, non-thermal treatment that aims to modify the composition of food material by partially removing water and air and impregnating it with physiologically active compounds without affecting the structural integrity of food matrix. Application of VI accelerates the mass transfer processes, which leads to few changes in food composition and improves dehydration. Large volumes in intracellular spaces of fruit and vegetable tissues make it suitable to introduce different agents like nutrients, cryoprotectants, browning inhibitors, enzymes, and chemicals; enhancing texture profile and inhibiting tissue softening, or compounds lowering water activity and pH. water activity Thus, the VI may help to achieve new product quality associated with physicochemical features and sensory attributes. This review highlights the evolution and mechanism of VI technique, major factors affecting VI of fruits and vegetables and their responses to processing, and industrial relevance. Vacuum impregnation consists ability to revolutionize various aspects of food processing and preservation. VI serves as a versatile tool that enhances the quality, shelf life, and nutritional content of processed fruits and vegetables. It offers unique advantages of altering product composition by introducing desired compounds while preserving structural integrity. VI improves mass transfer processes, reduces water content, enhances the absorption of nutrients, antioxidants, and preservatives. This technology finds application in producing fortified foods, extending shelf life, and creating innovative products with improved sensory attributes. VI's ability to efficiently impregnate substances into porous materials, combined with its energy-saving potential and compatibility with other processing methods, makes it a valuable tool in the food industry. As consumers demand healthier and long-lasting products, VI emerges as a promising solution for meeting market demands.

1. Introduction

Traditional processing methods used for conservation of fresh produce negatively affect sensorial and nutritive values. Fruits and vegetables (F&V) are enriched through various techniques for improvement of quality during post-harvest handling and value addition. Some of these techniques are encapsulation, freeze drying, ultrasonication, osmotic dehydration, and vacuum impregnation.

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In recent years, osmotic dehydration, despite being a simple process, achieved greater attention as an effective method for processing and preservation of F&V, as they have a greater number of pores to favor osmotic dehydration. This method is generally applicable in some F&V such as, banana, sapota, pineapple, mango, leafy vegetables, etc. with retention of quality characteristics (colour, aroma, taste, nutritional compounds, etc.). A further development in osmotic dehydration led to the development of vacuum impregnation (VI). The activity of hydrodynamic mechanisms (HDM) driven by pressure difference causes the exchange of internal gas or liquid trapped in open pores with an exterior liquid phase in a porous food product [1,2]. This technique was first launched to hasten osmotic dehydration processes subsequently, it has been employed to transfer desirable substances into porous matrix of food tissues in a controlled manner without affecting the integrity of the material [3]. Consequently, some mass transfer processes such as dehydration exhibit enhanced efficiency with minimal alterations to the food composition. To use it effectively, a comprehensive understanding of the product porosity and the capability of fluid penetration is essential. VI has broad applications in fruit and vegetable processing and provides many advantages as it contains a larger volume of internal gas in its pore space [4].

Due to its numerous benefits in the realm of food processing, this review all the aspects of the progression and workings of the VI technique. It covers the key factors influencing VI processes for F&V, advancements in VI applications within the industry, and the evaluation of physicochemical quality in VI-treated produce.

2. Evolution of VI

VI is a novel food processing approach, invented in the 1990s, that takes advantage of the features of food microstructure [5]. It gradually developed from the conventional osmotic process owing to the need to shorten process time. The distinction between osmotic dehydration and vacuum impregnation is given in Table 1. The three types of osmotic treatments are known as OD (osmotic dehydration), VOD (osmotic dehydration at vacuum pressure), and PVOD (pulsed vacuum osmotic dehydration) [6].

2.1. *Osmotic dehydration (OD)*

It is the process of partial water removal from the material by immersion in a hypertonic solution where water and solute move in the direction of concentration gradient at atmospheric pressure. OD was first mentioned in 1966 by Ponting et al. [7] and visualized two major synchronized counter-current flows, namely, i) water diffusion into the solution and ii) solute diffusion into the food. The major mechanisms involved are HDM and cell-matrix deformation (CDR) [8]. However, the leaching out of solute and nutrients from food tissues is the major disadvantage of OD. In 1994, Fito noticed a huge loss of nutrients while working on OD of orange peels. So, he thought of modifying the technology and thought of application of vacuum to OD and this led to the introduction of OD under vacuum [1].

2.2. *Osmotic dehydration under vacuum (VOD)*

The application of vacuum intensifies the capillary flow and favors the mass transfer rate during OD. It is probably caused by surface tension at the solid-solution interface [9]. Mass transfer occurs due to mechanically induced differences in pressures and this method is commercially called vacuum impregnation (VI). The major advantages of VOD include 1) the improvement of capillary force and mass exchange, 2) reduction in the processing time, 3) higher water loss and 4) lower solid gain rate. The major mechanisms involved here are hydrodynamic mechanism (HDM) and deformation relaxation phenomena (DRP) [These mechanisms are explained in Section 4]. Although Fito [1] succeeded in minimizing the processing time he also noticed that the rapid HDM was with the restoration of atmospheric pressure. So, he thought of restoration of atmospheric pressure and this led to the development of new technology that is known as “Pulsed Vacuum Osmotic Dehydration (PVOD)”.

Table 1
The distinction between osmotic dehydration and vacuum impregnation.

Osmotic dehydration	Vacuum impregnation
Mass transfer is dependent on the concentration differential between the intercellular fluids in the food material and the solution.	Mass transfer occurs as a result of a mechanically induced pressure difference.
The primary effect is the partial removal of water from the substance, which flows in the direction of the concentration gradient.	The main goal of this method has been to inject the external solution into the material.
Requires use of hypertonic solutions and occurs at atmospheric pressure.	Because vacuum is the only requirement, the solution could be isotonic.
The primary mechanisms at work are HDM and CDR.	The major mechanisms involved here are HDM and DRP
Prolonged process (hours/days).	The process is quick (min) and requires minimal energy.
Nutrient leaching from tissues is a major concern.	There is no nutrient leaching.
The most common osmotic solution (salt or sugar), significantly alters the taste and nutritional value.	There has been no such change in taste or nutritional value.
Osmatic solutions can only be used once.	External solutions can be reused multiple times, and it is possible to do so at low temperatures.
Results in reduced water content, leading to preservation and concentration of the food.	As a result of the incorporation of specific substances, the sensory, nutritional, or functional properties of the food are enhanced, as is the shelf life.

2.3. Pulsed vacuum osmotic dehydration (PVOD)

PVOD is also known as vacuum-assisted osmodehydration (ODVP). In PVOD, impregnation with osmotic solution occurs during the first 5–15 min of the process by the exertion of a vacuum pulse which causes a rapid change in composition of the product. These changes are governed by the osmotic driving force and mass transfer kinetics [3]. Subsequently, holding at atmospheric pressure for a long time leads to normal OD. Simply put, when vacuum impregnation is used at the start of OD, the procedure is known as pulsed vacuum osmotic dehydration (PVOD) [10,11]. It is a long-time process (days/week) and has got similar advantages as VOD treatment with a higher mass transfer rate. Here, the water loss rate is low, and solid gain rate is high. The major mechanism involved here is gas release and pore filling due to HDM [8,12,13]. The ODVP/PVOD process enhances the drying rate by decreasing the moisture content within the core of the osmodehydrated product. This reduction in central moisture diminishes the development of a sugary or solute-based hard crust during drying [14]. Moreover, using ODVP as a preliminary step before drying can significantly mitigate undesirable effects like browning, nutrient loss, or shrinkage. By boosting drying rates and curbing energy usage, ODVP presents a promising approach to improving food processing efficiency [15].

3. Vacuum impregnation system

Vacuum impregnation (VI) is a non-thermal, non-destructive treatment that aims to modify the composition of food material by partially removing water and air, and impregnating it with physiologically active compounds without affecting the material's structural integrity [3,6].

The schematic diagram and image of a lab-scale vacuum impregnation system are shown in Figs. 1 and 2. As shown in Fig. 1, the temperature of the jacketed vacuum chamber is controlled by water from a thermostatic bath and monitored by T-type thermocouples linked to the software. The pressure inside the chamber is reduced using a vacuum pump. This pump is linked to a proportional solenoid valve, coupled to a pressure transducer, and specialized software. The valve control and data collecting are handled by this customized program. At the bottom of the tank, a centrifugal pump is connected to recirculate the solution and continuously stir the impregnation solution. The vapor created by the vacuum treatment is condensed in a tank filled with silica gel [16].

4. Phenomena of vacuum impregnation

The VI process entails filling the free voids and capillaries in the produce to be treated with the appropriate substrate as a result of a mechanically generated pressure differential. The material is impregnated as a result of two phenomena *i.e.*, the hydrodynamic mechanism (HDM) and the deformation-relaxation phenomenon (DRP), both of these result in the filling of ideal intracellular capillaries [8,9]. Both HDM and DRP have an impact on achieving equilibrium, and their intensities are strongly associated with the three-dimensional food microstructure and solid matrix mechanical properties [17].

HDM is a mechanism of mass transfer, between porous food materials and surrounding liquid. This involves the infiltration of external fluid into the capillary pores and is regulated by the compression or expansion of internal gas. HDM is dependent on pressure gradients caused by changes in sample volume and/or externally driven at non-compartmented parts like intercellular spaces, capillary pores, and others [1,2,10]. Pressure change stimulates deformation (that could increase the volume of gas trapped in the pore) of the

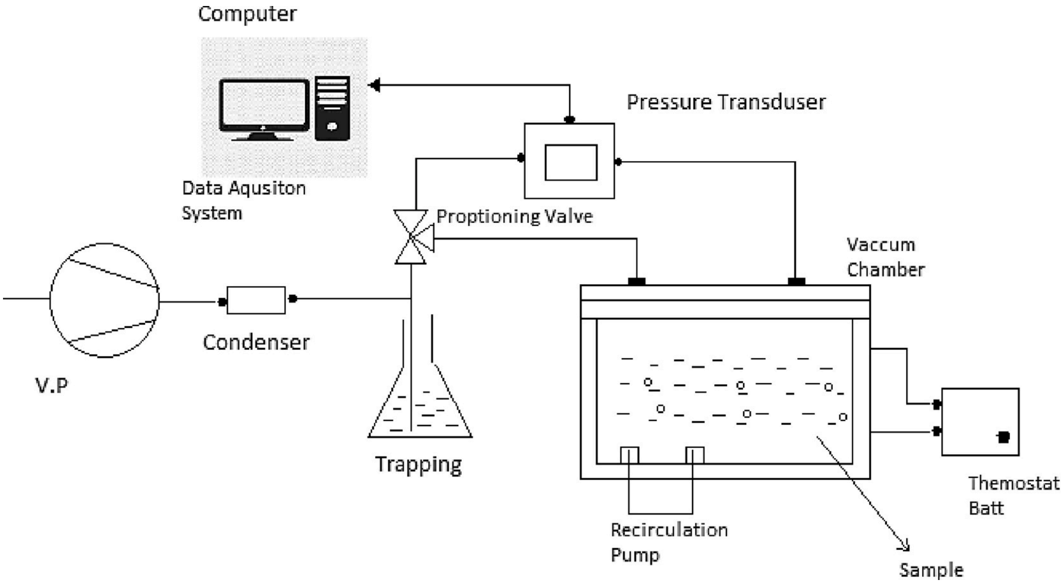

Fig. 1. Schematic diagram of vacuum impregnation system.

Fig. 2. Laboratory scale vacuum impregnation set-up.

sample volume due to the viscoelastic properties of solid matrix, which is called DRP. As suggested by, Fito et al. [18] DRP is affected by food microstructure and mechanical properties.

Explaining the accelerated mass transfer during VI through conventional osmotic and diffusion mechanisms poses challenges. Even the classical capillary mechanism does not effectively explain the relationship between vacuum pressure and mass transfer rate. Hence, to successfully scale up VI for industrial use, accurate predictive mathematical models are essential. These models enable process control, ensuring smooth operations. Effective models are crucial for understanding mass transfer kinetics, considering water loss and solute gain under negative pressure during VI [19]. Two mathematical models have been developed to understand the vacuum impregnation process in porous foods, considering their governing mechanisms. The initial model, rooted in HDM, was introduced by Fito [1] and later refined by Fito and Pastor [2]. The second model extends beyond HDM to include the DRP and considers the food material's viscoelastic properties [18]. The complete mathematical modeling and process optimization for industrial application is explained by Panayampadan et al. [20] in their insightful review paper.

5. Mechanism of vacuum impregnation

VI simply intensifies the rate of capillary flow and the mass transfer. When a porous structure is immersed in water then there is a

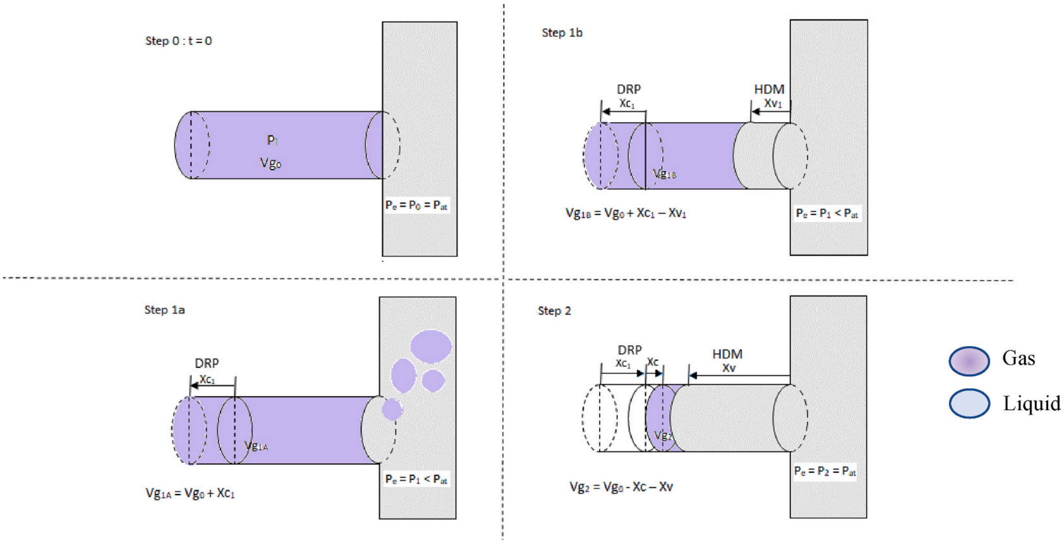

Fig. 3. Schematic representation of mechanisms (DRP & HDM) involved in filling up of capillary pores of fruit and vegetables with liquid in vacuum impregnation process.

Abbreviations: t_0 = Time required for internal and external pressure to become equal; p_1 = Vacuum pressure; p_2 = Final pressure p_i = Internal pressure; p_e = External pressure; p_{at} = Atmospheric pressure; Vg_0 = Initial volume of gas trapped in the capillary; Vg_{1A}, Vg_{1B}, Vg_2 = Volume of gas trapped into the capillary after each step of vacuum impregnation; Xc_1 = Increment of the volume of gas trapped in the capillary as a result of DRP; Xc = Decrement of the volume of gas trapped in the capillary as a result of DRP; Xv_1 = Partial decrement of the volume of gas trapped in the capillary as a result of HDM; Xv = Decrement of the volume of gas trapped in the capillary as a result of HDM.

fast mass transfer. This involves inflow of the external liquid throughout the capillary pores which is controlled by the expansion or compression of the internal gas. When low pressure is applied in a solid-liquid system followed by atmospheric pressure, hydrodynamic forces build up and are responsible for VI processes in the porous products. It occurs in the two stages *i.e.*, the phase of reduced pressure and the phase of atmospheric pressure. When the substance is submerged in isotonic solution (t_0), the pressure inside (p_i) and outside (p_e) of the capillary equalizes to atmospheric pressure ($p_i = p_e = p_{at}$). The capillary's initial volume (Vg_0) is filled with gas (step 0; Fig. 3).

5.1. Stages in vacuum impregnation process

5.1.1. Stage 1: reduced pressure step

The pressure is lowered in the first phase of the process ($p_1 < p_{at}$). The gas is evacuated from the capillary as a result of the pressure differential. The initial component of the deformation-relaxation phenomena (DRP) is caused by reduced pressure acting from the outside, which induces capillary deformation and expansion. The capillary volume is increased ($Vg_{1A} = Vg_0 + Xc_1$). This step continues till the pressure equilibrium ($p_i = p_e$) is achieved (step 1a; Fig. 3).

As a result of the HDM, the capillary begins to fill partially with liquid. The pressure within the capillary rises slightly, whereas the free volume inside is reduced to the value $Vg_{1B} = Vg_0 + Xc_1 - Xv_1$ (step 1b; Fig. 3).

5.1.2. Stage 2: atmospheric step

In the second phase of vacuum impregnation, the pressure returns to atmospheric norms. This leads the DRP to enter the relaxation phase. The capillary shrinks even more than it did before the process began. Simultaneously, as a result of capillary pressure and decompression, an intense inflow of fluid from the outside to the inside of the capillary is noticed, and the final volume of gas inside it falls to $Vg_2 = Vg_0 - Xc - Xv$ (step 2; Fig. 3).

DRP dominates the first stage while HDM dominates the second stage of the process when the impregnating solution penetrates the

Table 2
Internal and external factors affecting the vacuum impregnation process.

S. No.	Factors	Role and affect
Internal factors		
1.	**Structure of Food**	• As the intercellular space increases, the porosity increases leading to an increase in the rate of mass transfer due to HDM. • Fruits and vegetables, in general, have a higher porosity proportion than meats, fish, and cheeses, thus, making them ideal for VI methods. • Shape and size of the pores also affect the transport rate of HDM. • Mechanical properties of food like rigidity, elasticity, deformation, and compression rate affect the relaxation time and mass transfer kinetics of the solid matrix.
External factors		
1.	**Vacuum pressure**	• Effective pressure range between 5 and 60 kPa/50 to 50 mbar for minimally processed fruits and vegetables. • Promotes higher HDM and DRP. • High Water Loss (WL) rate can be obtained in low-pressure system. • Porosity increases with decrease in pressure.
2.	**Vacuum and Relaxation time**	• Higher the time higher will be the solid gain. • Both vary with the structure of products. • The vacuum time varies approximately between 2 and 30 min and relaxation time varies from a few minutes to several hours.
3.	**Types of external solution**	• Plant tissue cells behave differently when put in various solutions. • **Isotonic solution:** cells neither shrink nor swell. • **Hypotonic solution:** Water entering the cell will cause the cells to swell. • **Hypertonic solution:** Water exiting the cell causes the cells to shrink or shrivel. • As a result, the selection of VI solutions is dependent on the objective of osmotic treatment, i.e., the kind of final product.
4.	**Solubility of solutes**	• For highly soluble solutes, impregnation under vacuum is more. • Smaller the molecular weight of solute, the faster the diffusion. • Low molecular weight carbohydrates are commonly employed for VI processing of fruits and vegetables because they easily enter the sample matrix.
5.	**Concentration of solution**	• As concentration of solute increases, its diffusion into the matrix increases up to a threshold limit beyond which a negative impact on the final product such as shrinkage and excessive loss of some native liquids occur. • Sucrose is the most common isotonic solution used for minimally processed foods (20–50 °Brix) and dehydrated foods (50–75 °Brix).
6.	**Particle size of solution**	• Sub-micron particles maintain cloud stability by fitting within cellular pores, preventing precipitation or flow blockage in the porous matrix.
7.	**Temperature of solution**	• As the temperature of the solution increases the rate of impregnation. Higher temperature results in the final product's loss of flavour, colour, etc. • The most common solution temperature for VI is 20–50 °C.
8.	**Viscosity of solution**	• Higher viscous impregnation solution leads to reduced efficiency of VI process. • Higher viscosity slows down the solution transfer rate and increases time for impregnation and regain of gas/air in the pores at the final stage. leading to reduced final product quality. • Lower the viscosity of fluid, more effective the diffusion process of fluid into the porous tissue of fruits and vegetables.

material's structure. This is backed by deformation and compression of material [21]. From a practical perspective, the relaxation phase is crucial because only tissue impregnation occurs at this moment. Quick vacuum removal should be avoided because too rapid pressure equalization may cause capillary channel closure and hinder the hydrodynamic mechanism [1,4,18,22].

Table 3
Physicochemical changes in fruits and vegetables upon vacuum impregnation treatment.

Raw Material	Impregnating Solution	Effect	Reference
Dehydrated Mango	60 °Brix sucrose +2 g calcium lactate/100 g and 0 or 0.48 mL PME/100 g)	The lowest water loss and the highest soluble solid gain	[91]
Carrot and Eggplant	Lactic acid (pH-3.0); vegetable/solution mass ratio of 1:5	Improved pH reduction up to 20%; Eggplants showed greater impregnation phenomenon due to high porosity and low rigidity	[23]
Pineapple snacks	Calcium chloride (1g/100 mL)	Porous-and-crunchy snacks, with high glass transition temperature	[16]
Frozen lotus root slices	Maltose syrup	Increased the glass transition temperature; Altered the cellular component ratio; Freezing point declined; Higher retention of ascorbic acid	[44]
Mango cubes	Sucrose solution	VI facilitated weight loss and sugar gain; increase in intercellular space and cross-section area; degradation of protopectin was observed	[33]
Fresh cut Apple	Isotonic sorbitol, trehalose and sucrose solution	Higher firmness and crispness; Preserved from browning incidence; Enhanced stability, shelf life and sensory quality	[59]
Jujube	Calcium chloride (1% w/w) + PME (15 U/mL)	Higher firmness, soluble solids content, and ascorbic acid; Lower weight loss; Delayed degradation of pectin during storage	[92]
Fresh cut papaya	Calcium lactate (1% w/w) + PME (15 U/mL)	Increase in firmness/hardness and chewiness; slowdown in degradation of colour; enhanced shelf life	[37]
Kyoho grapes	2% calcium lactate	Increase in firmness; Higher calcium content; better texture	[93]
Chokeberry fruit	Apple-pear juice	Lower a_w; Low microbiological activity	[46]
Minimally processed potato	Rosemary oil	Higher weight gain (6–14%); improved microbial stability; No effect on texture and moisture; Persistence of EO aroma during storage	[38]
Fresh cut lotus root	Lactic acid bacteria (8–9 log CFU/mL)	Maintained texture and colour; Shelf-life extension up to 9 days	[72]
Frozen Strawberries	Trehalose (12 g/100 g) + AFP (0.2 g/100 g)	Significant improvement of freezing tolerance; The cryoprotection effect was influenced by the heterogeneity of the tissues.	[30]
Frozen Strawberries	Trehalose (12 g/100 g) + winter wheat extract (0.2 g/100 g)	PEF-VI enhanced cell viability and color retention (>30%); no effect on drip loss and texture	[83]
Frozen Watercress	AFP-type 1(0.01 mg/mL)	Improved cell wall definition with rounded cell shape; Smaller ice crystals; Less damage to microstructure; Higher turgidity; Improved texture after thawing	[29]
Red Raspberry	LMP (10 g/kg of solution) and calcium chloride (30 g/kg of pectin)	LMP-calcium is more effective than PME-calcium in improving fruit firmness; Enhance fruit structural integrity	[94]
Fresh-cut cantaloupe melon	Alginate-calcium coating solution	VI resulted in higher firmness and weight gain results; Has a significant effect on colour; Improved mechanical and structural properties	[95]
Ready to eat sweet potato	Polyphenol extract (95% [v/v] Proanthocyanidins)	VI resulted in a 473% increase in the concentration of phenolic compounds (200.23 mg EAG/100 g); Colour and texture remained stable; Wider sensory acceptance	[43]
Chinese red bayberries	2% Calcium ascorbate and 1% DSC	VI induced higher firmness; maintained a lower moisture loss, decay rate, PPO and POD activities, colour change and microbial growth; Enhance shelf life and sensory appeal	[71]
Dehydrated Sliced Tomato	NaCl (7.5%) + Sucrose (32.5%)	PVOD resulted in the highest value of water loss and weight reduction; Lowest solid gain, aw and moisture content	[96]
Chinese ginger	50% sucrose + 10% NaCl; solution/fruit mass ratio of 4/1	PVOD enhanced TPC, TFC, RSA and antioxidant activity; less browning due to inactivation of PPO and POD; better preservation of volatile profile	[34]
Minimally processed melon	5% Calcium lactate	Darker and more translucent appearance; Improved texture retention while storage; Microbial shelf-life reduced to 4 days	[73]
Potato chips	Calcium lactate and Zinc sulfate	Enhanced calcium (4.81%) and zinc (0.72%) content which can fulfil 10 and 21% respectively of 4–17 years age group.	[97]
Garlic slices	25% (w/w) NaCl	VUOD increased the formation of microscopic pores, and cell rupture; increased mass transfer	[14]
Frozen-thawed kiwifruit	30% Trehalose solution	PVI exhibited minimum drip loss (11.21%); Maximum ascorbic acid content (0.93 g/kg) and firmness (12.3 N); Retained the flavour and taste as well as improved water distribution	[31]
Apple cubes	Hibiscus anthocyanins	Enhanced anthocyanin content, (16–24.5%) in apple due to ultrasound-assisted VI at 100 Mbar pressure	[57]
Potato Fries	Ferrous ammonium sulfate hexahydrate	yielded 3.15 mg iron from 30 g fries; Provided reduced fat absorption by 17.7%; Better retention of colour; High crispness (0.37 kg/s) and firmness (0.39 kg/s)	[98]
Ash guard	Citrus peel polyphenols	~300% increase in phenols and antioxidant activity; no perceived bitterness in sensory analysis	[58]

Table 4
Practical application of vacuum impregnation in fruits and vegetable processing.

Raw Material	Impregnation Solutions	Effect	Reference
Fuji Apple	Calcium lactate solution	Calcium concentration increased by ten times; The final drying time was reduced from 8.5 to 6.5 h.	[50]
Pineapple snacks	Calcium chloride (1 g/100 mL)	91% Higher concentration of Ca^{2+} content in comparison to atmospheric pressure	[16]
Apple	Quercetin glycosides	Higher flavonoid uptake in the inner apple cortex ranging from 368 to 604 μg/g dry mass	[55]
Cranberry	Ascorbic acid	VI of bisected fruit significant increased ascorbic acid content; No effect of pressure on pH, soluble solid and anthocyanin content.	[5]
Low fat Potato chips	Calcium, Vitamin C & E	MI-VI enhanced the retention of 90% of calcium, 53% of vitamin C and 72% of vitamin E; High sensory acceptance	[87]
Chokeberry fruit	Apple-pear juice	Resulted in increased content of bioactive compounds (polyphenols); Higher antioxidant stability	[46]
Dried kale leaves	Onion juice + NaCl	VI showed protective action against nutritional properties and bioactive compounds especially antioxidant activity at 90 and 110 °C drying temperature	[99]
Minimally processed apple	Isotonic sucrose solution containing 1% green tea polyphenols and/or 1% ascorbic acid	Strong increase in antioxidant compounds and activity; Better colour preservation	[56]
Minimally processed melon	Probiotic, *Lactobacillus acidophilus* LA-3	VI was more efficient in incorporation and maintaining the viability; No effect on pH, acidity and soluble solids	[61]
Apple slices	Probiotic, *Lactobacillus rhamnosus* microcapsules	Probiotic survival reduced as fluid osmotic pressure increased; Vacuum pressure for 20 min promoted greater microbe impregnation	[62]
Fresh-cut potatoes	Ascorbic acid (AA) and calcium ascorbate (CaA)	AA-CaA had a significant anti-browning effect; VI maintained cell membrane integrity; Inhibited PPO, POD, PAL enzyme activity; Retarded chlorogenic acid generation	[51]
Fresh cut lotus root	Lactic acid bacteria (8–9 log CFU/mL)	Inhibited the enzyme activity and slowed down the physiological and biochemical reactions; Significant inhibitory effect on *E.coli* O157:H7	[72]
Jalapeño pepper pickle	Sodium chloride (10–15%) + acetic acid (2.7% w/w) + calcium chloride (0.2% w/w)	12% of $[NaCl]_{brine}$, 4.6 of brine to pepper mass ratio and 22 d of processing time was optimised for maximizing the solutes gain to water loss ratio and the process yield of whole pepper pickle	[100]
Turnip pickle	20% NaCl	VI improved the pickling speed and shorten the pickling time; increased firmness	[101]
Garlic cloves	Sodium chloride (80 g/kg + Sucrose (400 g/kg) + Vinegar (520 g/kg) + Acetic acid (35 g/kg); Garlic blubs to osmotic solution ratio (1:2 w/w)	PVOD promoted mass transfer of sodium chloride and acetic acid compared to the traditional OD method; It significantly decreased thiosulfinates content and L* values of garlic.	[102]
Apple	3% Ca-lactate, 3% lactic acid and 0.8% black carrot concentrate within 0.2 m mannitol	US-VI led to increases in calcium content (13.8%), total phenolics (11.8%), flavonoids (17.3%), anthocyanins (24.6%) and antioxidant capacities (23.6%); highest natural colour enrichment; Minimum cellular disruption;	[103]
Frozen carrot	Green tea extract (GTE) and trehalose	Blanching in trehalose and VI in trehalose and/or GTE limited the soluble solid and firmness losses through pre-treatments; Increase in TPC and AOA	[104]
Peach and sweet cherry	Aloe vera gel (100% v/v)	Delayed postharvest ripening process by retarding weight loss, colour changes, firmness loss; Increase of TSS; Delayed respiration rate and ethylene production	[105]
Osmotically dehydrated figs	Sucrose solution at 50 °Brix; solution/fruit mass ratio of 4/1	PVOD shortened the drying period; Resulting in reduced cost and energy saving	[11]
Dehydrated apple slices	Apple juice + 200 mg/L folic acid + 1.13 g/L calcium chloride	OH-VI (13 V/cm at 50°C- 5 kPa for 5 min) presented a high content of folic acid and its retention; maintained higher firmness and color value	[80]
osmodehydrated blueberries	65% (w/w) sucrose + 1.13 g/L of calcium chloride solution	OH-VI (13 V/cm at 40°C- 5 kPa for 15 min) improved mass transfer; enhanced polyphenols retention after drying; reduced the drying time	[81]
Whole potato	1% (w/w) iron (SunActive Fe and ferrous sulfate) solution.	US-VI increased the iron content by 210%; didn't adversely affect sensory evaluation, color, or texture	[78]
Whole potato	1% (w/w) iron (SunActive Fe and ferrous sulfate) solution.	PEF-VI increased the iron content by 457%	[82]
Garlic slices	25% (w/w) NaCl	VUOD enhanced solid gain and water loss; improved rehydration process; higher allicin content, improved color (ΔE), and enhanced firmness	[14]
Zucchini slices	Onion, kale, and onion and kale (50:50) juices with 3% NaCl solution	Enhanced bioactive compounds like quercetin (41.84 μg/g), carotenoids (276.04 μg/g), lutein and zeaxanthin (216.42 μg/g)	[52]

(continued on next page)

Table 4 (*continued*)

Raw Material	Impregnation Solutions	Effect	Reference
Vacuum-cooked pumpkin discs	Ferrous gluconate (FeGlu) solutions containing β-cyclodextrin (BCD) and/or ascorbic acid (AA)	VI elevated iron content (17–20 mg Fe^{2+}/100 g), a 30-fold increase compared to non-impregnated discs; did not affect moisture content and pH	[53]
Cut apple cubes	Isotonic solution of 0.5% ascorbic acid, 0.5% citric acid, and 10% sucrose	Raised ascorbic acid content (73.5–130 mg/100 g) by 3–25 times and caused a 15%–34% mass gain. pH decreased by around 20–30%	[47]
Osmodehydrated apple	40 °Brix grape juice	ODVP Resulted in higher total soluble solids, lower moisture content and faster drying rate; reduced case hardening	[15]

6. Factors affecting the vacuum impregnation process

Tissue impregnation is influenced by the vacuum pressure used, duration of the vacuum, relaxation stages, and liquid viscosity coefficient. The quantity of vacuum that allows native fluids to exit tissue is intimately connected to the morphological and porosity features of raw materials [5,21,23,24]. The internal and external factors governing the VI process are given in Table 2. The kinetics of gas outflow, deformation-relaxation phenomena, and liquid influx are all significantly influenced by the impregnated tissue characteristics [18].

Further, Petersen (2014) [25] classified the factors affecting the process management of VI into three sections namely process condition, product characteristics, and solution composition. Researchers and food technologists can be able to manipulate and manage the VI process using these factors to modulate infused fruit and vegetables according to industrial and consumer needs. These factors include.

1. **Process conditions:** Pressure, time, temperature, agitation, sonication, product/solution ratio.
2. **Product characteristics:** Porosity, firmness, cell arrangement, intercellular spaces, surface/volume ratio.
3. **Solution characteristics:** Osmotic pressure, rheological characteristics, additive characteristics.

7. Vacuum impregnation induced physicochemical changes in fruit and vegetables

Because of the large volume of intracellular spaces in food tissues, the following agents may be introduced into them.

- Cryoprotectants,
- Browning inhibitors,
- Enzymes,
- Texturizing agents, and
- Compounds lowering water activity and pH

Thus, using VI may lead to new product quality associated with physicochemical features and sensory attributes. The alteration in the F&V does not destroy their cellular structure instead ensures mass transfer during OD and modifies the physicochemical characteristics of the material, both of the characteristics have a significant impact on the technological processing of fruits and vegetables [21]. The responsiveness of numerous F&V to VI processing in terms of physicochemical changes is described in Table 3 and Table 4. The impregnated sample volume fraction, sample relative volume of deformation, and effective porosity are all substantially influenced by raw material properties (maturity, porosity, size, and shape) and VI conditions (solution type and concentration, vacuum pressure, relaxation time and food/solution mass ratio) [9,26]. Texture, total acids, water activity, and color are highly affected by VI as a consequence of a change in product density, notably in highly porous food samples [27]. Following application in different F&V, the benefits of VI have been identified for desired product characteristics like improved nutrition retention, fresh-like sensory attributes, enhanced shelf life, and shortening of process time [16,28].

7.1. *Microstructure changes*

VI under controlled conditions alters the microstructure, it was observed by Cruz et al. [29] in frozen watercress that VI of AFP-I solution improved cell wall definition with rounded cell shape due to smaller ice crystals formation. This is most likely owing to hydrogen interactions between water molecules and AFP-I, which disrupt normal ice crystal net formation. Hence, leading to lower damage to microstructure. Furthermore, VI with APFs reduces water drip loss in freeze-dried products during thawing and also preserves cell viability by reducing the damage caused by ice crystals [30]. Similarly, Chen and Fan [31] reported decreased drip loss during thawing in trehalose-impregnated kiwifruit due to improved water-holding capacity of cryoprotectant and reduced damage by ice crystals. VI also enhances structural integrity by infusion of calcium into the cell matrix [32]. It is to be noted that, higher vacuum pressure may damage the microstructure of the matrix as observed in mango cubes [33] that, VI enhanced the intercellular spaces and cross-sectional area due to the alterations in mango tissues strongly correlating with the changes in water and solute mass transport. Feng et al. [14] proposed a novel technique for OD of garlic slices, known as Vacuum Ultrasonication Osmotic Dehydration (VUOD). The findings demonstrated that VUOD exhibited depletion of intercellular air and improved mass transfer rate during the OD process of garlic slices in comparison to both OD and VOD methods due to enhanced formation of microscopic pores, and cell rupture within garlic slices. LF-NMR analysis further quantified moisture movement across vacuoles, cytoplasm, intercellular spaces, and cell walls of garlic cells due to microstructure changes.

7.2. *Sensory changes*

VI enhances sensory characteristics by improving and/or preserving the color, volatile profile, and taste of the final product. It inhibits enzymatic browning by inhibiting polyphenol oxidase (PPO) and peroxidase (POD) activity [34,35] and eliminates bitter taste. In case of dark-colored fruits, a small change in hue noticed, whereas in light-colored fruits the color is well preserved. Color variations caused by VI are associated with a rise in clarity and loss of color chrome, which is comparable with the gain in transparency [36]. In VI-treated papaya cubes, a slow decline in luminosity and chroma values was observed during storage due to the slower degradation of carotenoids, hence maintaining the stability of pigment [37]. VI is also effective in preserving the aromatic profile during storage which has been demonstrated in potatoes impregnated with rosemary oil [38].

VI enhances textural attributes like crispness, rigidity, brittleness, and fracturability. The texture quality of VI products is significantly related to the type of VI solutions used. Higher the solid gain higher the texture hence, VI enhances textural stability by increasing solid gain and water loss [27,39]. Improvement in the tissue structure and microstructural integrity can be achieved by impregnating texture modifiers such as calcium [36,40]. Calcium ions impregnation reduces pectin degradation in middle lamella by interacting with pectin in the cell walls of plant tissues, increasing the hardness of cell structures and helping to maintain or create specific textural properties in impregnated products, hence maintaining the texture of fruit and vegetables during storage. Li et al. [41] found similar outcomes when Chinese red bayberry infused with a solution of calcium ascorbate and disodium stannous citrate. The rise in firmness values was linked to the formation of crosslinks due to calcium impregnation, connecting carboxyl groups. To enhance the texture of raspberry fruits, a combination of calcium (30 g calcium/kg of pectin) and low-methoxyl pectin (10 g/kg of pectin) was employed. The infusion of this mixture into fruit pieces during VI (50.8 kPa for 7 min) outperformed the OD process, leading to faster, more even impregnation. This approach notably enhanced the firmness and overall structural integrity of red raspberries [32]. VI can also be used to mitigate chilling injury by enhancing proline content and antioxidant activity in spinach leaves by impregnating salicylic acid and GABA [42]. The sensory assessment of ready-to-eat sweet potatoes VI with proanthocyanidins received greater approval among individuals who appreciated the distinct flavor of the vegetable. Consumers characterized these prepared sweet potatoes as having a firm, juicy, and sweet texture [43].

7.3. *Thermal properties*

VI enhances thermal conductivity, glass transition temperature (Tg), and thermal diffusivity coefficient which further enhances the stability of the product during storage [16,44]. It enhances freeze tolerance and mitigates freeze damage by impregnating it with cryoprotectants [30]. Martínez-Monzó et al. [45] observed a 15–24% rise in apple thermal conductivity after treatment with isotonic sucrose solution, accompanied by a slight diffusion coefficient increase. The enhanced thermal conductivity might result from solution replacing gases in intercellular spaces, while a minor diffusion coefficient increase could be due to simultaneous product density elevation. Lima et al. [16] reported in calcium-impregnated pineapple snacks that the VI process exhibited greater endothermic peak temperature which is strongly associated with the sugar and acid matrix. These higher Tg values in impregnated pineapple samples were ascribed to higher calcium concentrations, which resulted in less plasticizing action of water. The increased Tg enhances the physical and chemical stability of the dried food, particularly in terms of lipid oxidation, enzymatic activity, minimal enzymatic browning, and structural preservation. Similarly, maltose syrup vacuum-impregnated frozen lotus root slices significantly enhanced the Tg. In addition, VI modified the ratio of cellular components, and replaced certain water molecules, resulting in reduced melted water, decreased crystallization rate, freezing point, latent heat, and apparent specific heat [44].

7.4. *pH and water activity*

The raw material's nature, as well as the kind and concentration of VI solutions, affects product acidity and water activity but in general, VI reduces pH and water activity. Reduced pH further reduces thermal resistance and growth rate of microorganisms leading to microbial stability [23,46]. Reduced water activity in tissues leads to decreased free water available for the growth of microorganisms and reduces moisture content in raw material shortening the drying time of dehydrated food and increasing Tg in frozen food. To decrease the water activity in the final product, the impregnation solution should be in a range of 30 to 60° Brix [9]. Most microorganisms thrive when water activity surpasses 0.95, and the minimum water activity conducive to microbial growth is 0.6. To lower the pH of treated foods, weak organic acids such as lactic acid, ascorbic acid, and malic acid are frequently employed. In their research, Derossi et al. [23] investigated the impact of vacuum acidification (VA) on pH reduction and its kinetics in carrot and eggplant slices. In the case of eggplants subjected to VA, they achieved a pH decrease of 20% by applying a pressure of 100 mbar for a vacuum duration of 3 min, followed by a relaxation period of 5 min. In contrast, a mere 3% reduction in pH was observed under atmospheric pressure. The hard structure of carrot tissues limited the deformation-relaxation interactions during both vacuum and relaxation phases, resulting in minimal pH changes. Similarly, VI had a notable impact on the pH of apple cubes, leading to a significant reduction of approximately 20–30%, as evidenced by a study conducted by Kidoń et al. [47]. The vacuum-impregnated pineapple snacks with calcium exhibited a notable reduction in water activity compared to the control samples. This decline could be attributed to the influence of Ca^{2+}, leading to a decrease in free water content. This difference persisted throughout the remaining drying phase, culminating in a final water activity of about 0.390 for the vacuum-impregnated samples and 0.506 for the control samples [16]. According to Nawirska-Olszańska et al. [46] water activity was assessed for chokeberry fruit impregnated with apple-pear juice and subjected to drying. The dried samples exhibited very low water activity levels, ranging from 0.144 to 0.207, with slightly higher values observed for non-impregnated fruit (0.284). A similar reduction in water activity and moisture content in ODVP pre-treated apple slices compared to the ones pre-treated with OD [15]. This disparity can be attributed to the higher concentration of impregnated solutes present in ODVP.

8. Industrial relevance in fruits and vegetable processing

VI can be employed for multifaceted functions in the food processing industry, some of which are discussed hereunder.

8.1. Fortification

VI is reported to be the best tool for food fortification processes. Dietary supplements, bioactive ingredients such as vitamins and minerals, and other desirable solutes can be introduced into fruit and vegetable products without compromising their integrity using this technique [48]. Iron content in VI potatoes increased with vacuum time and recovery time [49]. Many calcium salts such as calcium chloride, calcium phosphate, and calcium lactate can be used to fortify fruits. For instance, calcium can be infused into the cell structure of pineapple snacks up to 91% using vacuum pulse OD [16]. In their study, Yılmaz and Ersus Bilek [26] found that US-VI (130 W - 211 mmHg) maintained cellular integrity while significantly enhancing calcium content (13.8%), total phenolics (11.8%), total flavonoids (17.3%), total anthocyanins (24.6%), and antioxidant capacities (23.6%) in apple discs, as compared to VI alone. Assis et al. [50] studied mass transport dynamics during impregnation of sliced apples with calcium lactate in a vacuum chamber to produce fortified snacks. Calcium concentration increased 10-fold in the impregnated samples and vacuum intensity did not make a significant difference in calcium content. Impregnation of ascorbic acid (AA) and calcium ascorbate (AA-CaA) in cut potato subjected to vacuum for 2 min showed anti-browning effect. VI treatment not only maintained cell membrane integrity and inhibited key enzymatic activities of PPO, POD, and phenylalanine ammonia-lyase (PAL), but also delayed the formation of phenolic substrates, especially chlorogenic acid. On the other hand, VI promoted the penetration of AA-CaA solution into potato tissue and delayed the loss of AA [51]. The study conducted by Kręcisz et al. [52] on zucchini slices for VI at 6 kPa pressure using freshly extracted juices from onion, kale, and a blend of onion and kale (50:50) along with a 3% NaCl solution. Among the treatments, the application of VI with onion and kale juices led to notable improvements in bioactive content. Zucchini impregnated with onion juice and subsequently freeze-dried exhibited the highest levels of quercetin (41.84 μg/g DM) and carotenoids (276.04 μg/g DM). On the other hand, zucchini treated with kale juice and subjected to convective drying displayed the highest values of lutein and zeaxanthin (216.42 μg/g DM). Recently, Lencina et al. [53] investigated iron content and bioaccessibility in vacuum-cooked pumpkin discs (VCPD) impregnated with ferrous gluconate (FeGlu) solutions containing β-cyclodextrin (BCD) and/or AA. Application of vacuum pressure of 800 mbar for 25 min followed by atmospheric restoration for 25 min, pumpkin discs immersed in FeGlu solutions showed elevated iron content (17–20 mg Fe^{2+}/100 g), a 30-fold increase compared to non-impregnated discs. "*In vitro*" simulation revealed that both BCD and AA positively affected iron solubility and stability of ferrous iron form, resulting in Fe^{2+} bioaccessibility of approximately 17% and 20% w/w, respectively. Hence, VI offers possibilities for improved nutritional fortification of fruit and vegetables.

8.2. Polyphenol and bioactive compound enrichment

The content of bioactive compounds was increased in chokeberry fruits subjected to vacuum impregnation with apple-pear juice followed by drying using microwave-vacuum technology. About 20 polyphenolic compounds including anthocyanins, flavonols, phenolic acids, and flavan-3-ols were identified in these fruits [46]. Similarly, VI improved the bioactive content in dried kale leaves [54] and ready-to-eat sweet potatoes [43]. Schulze et al. [55] enriched apples with quercetin glycosides from apple peel by VI. Quercetin content varied between 368 and 604 μg/g dry mass in VI apples. The use of low SSC solution resulted in increased quercetin enrichment in contrast to apple pectin solutions with elevated viscosity. Tappi et al. [56] used an isotonic sucrose solution containing 1% green tea extract (GTE) to increase the levels and activity of antioxidant compounds of minimally processed apples by VI. However, GTE-treated apples were slightly affected by a higher degree of browning development during storage. Impregnation of sweet potatoes with a polyphenol extract of 95% (v/v) proanthocyanidins, increased the concentration of phenolic compounds in the treated samples by 473%. VI has enabled the production of a product that provides approximately 220.0 mg of gallic acid equivalents (GAE/100g) of polyphenols per 100 g per serving, a value similar to polyphenol-rich vegetables [43]. Recently, Dinçer [57] developed an innovative product i.e., hibiscus anthocyanin-impregnated apple cubes through US-VI (100 mbar for 30 min) to enhance the polyphenol content and to provide attractive color in the final product. The apple cubes had 16–24.5% more anthocyanin content through the US-VI process when compared to the VI. The VI method was effectively utilized to infuse citrus peel polyphenols into ash gourd, resulting in improved functionality [58]. Through optimization, it was determined that blanching for 2.21 min, followed by VI at a pressure of 432.31 mbar for 28.18 min, led to a substantial increase in total phenolic content by approximately 300%, total flavonoid content by around 140%, and antioxidant activity by approximately 300%. Panelists did not detect any significant increase in bitterness in the infused ash gourd. Hence VI did not negatively impact its physicochemical and sensory characteristics.

8.3. Minimally processed food

Minimally processed F&V are products that retain the quality attributes of fresh produce. By properly formulating the impregnation solution and rapidly changing the composition of the solid matrix, VI can aid in the development of high-quality and stable minimally processed products. VI with rosemary essential oil on a minimally processed potato product resulted in an innovative fresh-cut potato product and the weight gain was promoted in the range of 6–14%, depending on the concentration of rosemary essential oil [38]. Neri et al. [59] developed a high-quality apple cube by VI with an isotonic solution which favorably improved the physical and sensory qualities and reduced the negative impacts on the mechanical properties and color of the fresh-cut apple. Another study by Mierzwa et al. [5] demonstrated VI's efficacy in enriching ascorbic acid (AA) content in heat-treated or bisected cranberry fruits, with the process parameters of lower pressures and/or extended impregnation times playing a role. In a recent study conducted by Kidoń et al. [47] apple cubes were VI with isotonic solution (0.5% AA, 0.5% citric acid, and 10% sucrose). VI conditions included a 10-min vacuum at 15 kPa, followed by restoration for 5 min and a 10-min relaxation period at atmospheric pressure. VI notably raised AA content (73.5–130 mg/100 g) by 3–25 times and caused a 15%–34% mass gain. Additionally, VI has the potential to mitigate color deterioration and browning in cut apple tissue. A strong negative correlation was observed between the mass gain and the firmness of fresh apple cubes ($r = -0.85$).

8.4. Introduction of probiotics into fruits

Probiotics have been defined as live microbial food ingredients that have beneficial effects on human health by improving the microbial balance in the intestine [60]. This type of bacteria for human consumption usually belongs to the group of *Lactobacilli* or *Bifidobacteria*. Betoret et al. [60] reported probiotic-enriched dried fruits using VI technique either with commercial apple juice containing *Saccharomyces cerevisiae* or with whole milk or apple juice containing 10^7 or 10^8 cfu/mL of *Lactobacillus casei* (spp. rhamnosus). It was reported that dried apple samples could contain about 10^6 cfu/g *L. casei* (spp. *rhamnosus*). This is similar to levels found in commercial dairy products. The addition of *Lactobacillus acidophilus* LA-3 (1.4×10^{10} CFU g^{-1}) to minimally processed melon through VI had probiotic claims found commonly in dairy products. The incorporation of probiotics did not affect pH, acidity, and soluble solids, but did affect fruit firmness [61]. Flores-Andrade et al. [62] studied the incorporation of probiotics (*L. rhamnosus)* protected in a double emulsion by OD and VOD into apple slices. Greater impregnation of microorganisms was facilitated by using a vacuum treatment period (20 min). Murta berries treated with *L. casei* for probiotic-enriched dried snacks showed around 10^7 CFU/g viable population at 150 mbar vacuum pressure and 15 min vacuum time [63]. Akman et al. [64] investigated *L. paracasei*-infused apple slices dried via conventional and vacuum methods at 45 °C, and stored for 28 days at 4 °C. Probiotic inoculation levels were 7.42 and 7.99 log CFU/g, maintaining populations above 6 and 7 log CFU/g for vacuum and oven drying, respectively. The probiotic-enriched dried apple snacks had favorable sensory and bioactive qualities during storage. VI was also suggested to achieve *L. paracasei* populations of up to 9 log CFU/portion in apple snacks with a 30-day shelf life and 10^6–10^7 CFU/g of *Lactiplantibacillus pentosus* in table olives [65,66].

8.5. Pretreatment

Freezing is a conventional method of preserving F&V. It better retains nutrients and improves texture quality in the final product than those other means of preservation. VI with cryoprotectants (usually hypertonic sugar solution) or cryostabilizers (high methoxyl pectin and glycerol) reduces the quantity of freezable water, thus minimize drip loss during thawing and also lowering the ice crystal damage in frozen products. Osmosis in hypertonic solution occurs simultaneously due to the combined effect of pressure gradients and capillary action [27,67]. Utilizing VI as a pre-treatment before freezing serves two primary purposes: reducing moisture content before final drying to conserve energy and incorporating functional solutes such as anti-microbial, antioxidant, and anti-browning agents to enhance product quality [68]. A study by Chen and Fan [31] on kiwifruits treated with PVOD with 30% trehalose, followed by freezing and storage at −20 °C exhibited minimum drip loss (11.21%), maximum AA content and firmness and retained the flavor and taste as well as improved water distribution for frozen-thawed kiwifruit. This finding suggests that PVOD with trehalose could effectively enhance the quality of frozen-thawed kiwifruit. Romero et al. [69] reported that VI of calcium in raw olives has the potential to mitigate weight loss and even lead to weight gain, all the while preserving firmness during table olive processing. In the case of Manzanilla and Hojiblanca olive cultivars, VI resulted in approximately 10% and 4% mass gains, respectively. Furthermore, VI did not adversely affect the color or flavor of the olives. Thus, VI emerges as a promising pre-treatment method for the processing of table olives. Similarly, González-Pérez et al. [15] investigated the impact of osmodehydration (OD40) and pulsed-vacuum osmodehydration (ODVP40; 40 °Brix grape juice at 40 °C and 498 mmHg) as pre-treatments before apple drying. OD40 exhibited a slower drying rate compared to ODVP40 due to initial moisture and solute distribution. ODVP40 resulted in higher total soluble solids, lower moisture content and faster drying rate. The vacuum pre-treatment in OD effectively reduced case hardening by minimizing moisture concentration within the product.

8.6. Food salting

The combination of VI with brining processes has been developed as a means to enhance the efficiency of brining by accelerating salt uptake through HDM. VI can lead to more even salt distribution within the product, thereby achieving rapid salting kinetics and increased process yields in the salting of porous foods [70]. VI before pickling promotes high salt gain in a short processing time and reduces water loss. A study was conducted on the vacuum impregnation of turnip with 20% NaCl (salt) during the pickling process. Quality parameters of VI turnips changed rapidly compared to those subjected to atmospheric impregnation containing different volatile compounds than traditionally treated pickles. This concludes that VI can improve pickling speed and reduce pickling time, but must be integrated with microbial fermentation to preserve the original flavor of pickled vegetables [71]. Feng et al. [14] reported that water loss and solid gain in salted garlic slices (25% (w/w) NaCl for 2 h) subjected to VUOD were notably higher (21.12% and 6.10% respectively) compared to those treated with conventional OD (10.67% and 5.54% respectively) and VOD (14.18% and 5.48% respectively). As a result, garlic slices treated with VUOD exhibited superior quality attributes, including higher allicin content, improved color (ΔE), and enhanced firmness, in comparison to samples treated with OD and VOD methods. Therefore, integration of VI with brining processes or as a pre-treatment for pickling holds potential for enhancing salt absorption, reducing water loss, and improving the quality attributes of various food products.

8.7. *Shelf-life extension*

By strategically combining vacuum impregnation (VI) with various techniques and agents, the shelf life of food products can be significantly extended. Through partial water removal, impregnation of organic acids to lower pH, and the incorporation of antimicrobial and antioxidant agents, along with storage at low temperatures, product shelf life can be effectively prolonged. For instance, isotonic solutions containing sorbitol, glucose, fructose, sucrose, trehalose, and maltose have been used at 738 mbar for 10 s to facilitate the penetration of water as an impregnating agent. This approach improved the shelf life of fresh-cut apples while having minimal impact on fruit composition and quality. Moreover, it helped prevent the browning of apples [59]. Combining calcium ions with pectin methylesterase (PME) has proven effective in enhancing the quality of freshly cut papaya and extending its shelf life [37]. Similarly, VI with probiotics (lactic acid bacteria; 8–9 log CFU/mL) extended the shelf life of fresh-cut lotus root up to 9 days [72]. The probiotic fermentation solution exhibited the ability to inhibit the proliferation of *E. coli* and enzymes like PPO, POD and PAL. This inhibition led to a deceleration of physiological reactions, which ultimately aided in preserving the texture and color of the tissues. The lactic acid bacteria not only countered other microorganisms but also contributed to ongoing preservation through the production of metabolic acids during storage hence enhancing shelf life. However, it's important to note that VI may sometimes have contrasting effects on shelf life. Tappi et al. [73] observed a reduction in shelf life for minimally processed melon treated with VI, where the shelf life was shortened from 7 days (control) to 4 days. This reduction was attributed to the deformation-relaxation events that occur when vacuum pressure is applied, irreversibly altering the viscoelastic properties of fruit tissues. Such modifications could potentially increase the availability of nutrients for microbial growth, thereby decreasing shelf life.

8.8. *Energy saving*

By reducing the volume of the products, VI saves the cost of food processing, storage, and transport. Also, as VI removes most of the water from the product, energy consumption has been found to be decreased by the pretreatment of F&V with VI [74]. The use of a vacuum at the start of OD increases both water loss and osmotic solute uptake. As a result, VI is suggested as an energy-saving pre-treatment before drying, freezing, and pickling of various F&V. Energy savings can be obtained by eliminating intercellular water without using heat, and further removal of water all across the dehydration process consumes less energy than in non-impregnated products [75]. To support this, Sun et al. [76] reported that, US-VI reduced the drying time of ginger slices by 59.75%. Thereby reducing the energy by more than half required for drying the same during normal OD. This highlights VI's potential to significantly enhance energy efficiency in food processing operations.

The practical application and/or industrial relevance of vacuum impregnation in fruits and vegetable processing is depicted below (Table 4).

9. Recent innovations in vacuum impregnation

Various cutting-edge techniques, including microwave, ohmic heating, pulsed electric fields, electron-beam irradiation, high-pressure treatment, and ultrasound, have been examined for their potential to boost the effectiveness of VI in F&V. These methods are often applied as pre-treatments, post-treatments, or in combination with VI, resulting in notable structural changes that swiftly affect mass transport processes, lead to considerable solute uptake, and create shelf-stable products, or enhance overall process efficiency [26,77].

9.1. *Ultrasound-assisted vacuum impregnation (US-VI)*

Ultrasound-assisted technologies' efficacy in food applications primarily stems from cavitation force, involving the formation, expansion, and collapse of gas-filled bubbles due to pressure fluctuations from acoustic waves (16 kHz–100 MHz). The microbubble implosion did not rupture cellular integrity but led to mechanical outcomes, like enhanced mass diffusivity and transfer phenomena [26]. This process creates microscopic channels that facilitate the exchange of substances in the food matrix due to increased cell wall permeability [57]. Consequently, ultrasound holds great promise for vacuum impregnation processes. In the study by Mashkour et al. [78] it was demonstrated that both VI, as well as US-VI (37 kHz with 140 W of power intensity for 24 min- 3.5 kPa for 37 min), significantly increased the iron content in whole potatoes by approximately 137.5% and 210%, respectively. For fortified-cooked potatoes, SunActive Fe showed 73% relative bioavailability compared to ferrous sulfate's 86%. However, this discrepancy didn't adversely affect sensory evaluation, color, or texture of the fortified potatoes. Mierzwa et al. [5] enhanced the infusion of ascorbic acid in cranberry fruit involves the combined use of US-VI. The application of US-VI resulted in increased ascorbic acid content, reduced relative color difference, and enhanced antioxidant properties. The effectiveness of impregnation varied significantly, contingent upon the utilization stage of ultrasound. In a recent investigation by Sun et al. [76] the effects of different osmotic pretreatments using NaCl, such as OD, US, US-VI, and vacuum freeze-drying combined with hot air drying (FAD), were examined on ginger slices. The findings demonstrated that the combination of US-VI and FAD reduced the drying time by 59.75%. Rehydrated ginger treated with US-VI-FAD exhibited a reduced total color difference (5.65), a higher rehydration rate (4.89), and an aroma closer to that of the fresh sample. Further, US-VI-FAD samples exhibited elevated levels of gingerol, 6-gingerol, and total antioxidant activity.

9.2. Ohmic heating-assisted vacuum impregnation (OH-VI)

Ohmic heating (OH) is a thermal technique where the food material, acting as an electrical resistor, is heated via an electric current. This process rapidly and evenly heats the material as electrical energy transforms into heat. During OH treatments, applying a moderate electric field (with lower field strength and frequencies) can facilitate improved diffusion through electric field treatment. This method increases cell membrane permeability and enhances mass transfer, which can support VI treatment in effectively impregnating nutrients into the food matrix [79]. OH-VI (13 V/cm at 50°C- 5 kPa for 5 min) presented a high content of folic acid and its retention, while maintaining higher firmness and color values in apple snacks [80]. Furthermore, another study by Moreno et al. [81] examined the impact of OH and PVOD on the dehydration process and retention of polyphenol compounds in osmodehydrated blueberries. The study involved using a 65% (w/w) sucrose solution, applying an electric field of 13 V/cm (100 V) at 40 °C, conducting PVOD at 5 kPa for 15 min, followed by air drying at 60 °C. OH-VI notably enhanced mass transfer maximized retention of phenolic components, and decreased the overall drying time.

9.3. Pulsed electric field-assisted vacuum impregnation (PEF-VI)

Pulsed electric field (PEF) is a non-thermal technique that operates by inducing electroporation in cell membranes. Short bursts of high-voltage electric fields lead to enhanced permeability of cell membranes with minimal loss of nutrients. PEF serves as a pre-treatment for processes such as extraction, drying, freezing, and salting, owing to its ability to accelerate mass transfer. PEF treatment can improve mass transfer by promoting the release of intracellular fluids through membrane disruption. Utilizing a PEF pre-treatment before VI could potentially enhance the effectiveness of VI-fortification processing [77]. Mashkour et al. [82] found that the iron content of VI and PEF-VI (394 V/cm with 36 pulses-3.5 kPa for 37 min) processed potatoes increased by approximately 126% and 457%, respectively, compared to untreated potatoes. PEF pre-treatment substantially enhanced impregnation during VI processing. The effectiveness of VI was positively influenced by higher PEF intensity and increased pulse number. Notably, research employing PEF-VI (850 V/cm- 86 kPa) on frozen or thawed strawberries to impregnate cryoprotective solution (trehalose and winter wheat extract) demonstrated enhanced cell viability and color retention (>30%) [83].

9.4. High pressure-assisted vacuum impregnation (HP-VI)

High-pressure processing can serve as an infusion technique on its own. By subjecting F&V to high hydrostatic pressure, the cell structure is altered, leading to increased permeability. This effect can be advantageous for improving the absorption of bioactive substances from the surrounding solution. Pressure-induced structural changes in food can impact diffusion coefficients, potentially speeding up the mass transfer rates of components into the food without significantly altering its matrix [84]. In a recent study conducted by Gao et al. [85] high HP-VI was applied to carrots that had been impregnated with a pigment. The combined use of VI and high hydrostatic pressure at 100 MPa for 5 min achieved complete impregnation of the color solution into the carrots. Simultaneously, this approach minimally affected the integrity of cell membranes and conserved the texture of the carrots.

9.5. Microwave-assisted vacuum impregnation (MI-VI)

Microwave drying offers the advantage of reduced drying time and enhanced quality for dried materials. It employs microwave radiation within the frequency range of 0.3 GHz–300 GHz to generate heat in a chamber under controlled pressure conditions, typically ranging from above the triple point of water to below atmospheric pressure (101.33–0.61 kPa) [86]. Duarte-Correa et al. [87] enhanced the nutritional value of potato slices by MI-VI (1.7 W/g- 4 KPa, for 3 min) of calcium, vit C, and vit E. The fortified potato chips were found to have significantly higher amounts of calcium, vit C, and vit E compared to the control group where VI samples were subjected to microwave treatment as a post-treatment step. They also discovered that microwave vacuum drying, under specific conditions, resulted in an average retention rate of over 90% for calcium, 53% for vitamin C, and 72% for vit E. Moreover, the potato snack produced received positive feedback in terms of sensory acceptance. In a parallel exploration by Pasławska et al. [88] apple cubes were subjected to VI (0.01 MPa for 4.5 min) followed by microwave-vacuum drying (480 W). Findings indicated that VI led to enhanced drying kinetics. The MI-VI treatment resulted in lower water activity, higher dry matter, increased bioactive compounds, and antioxidant activity, along with reduced drying time compared to the control. However, the impregnated apples exhibited darker, more yellow coloration and were more prone to deformation or cutting than non-impregnated ones.

9.6. Electron-beam irradiation-assisted vacuum impregnation

Electron-beam irradiation offers a dual benefit to fresh produce, as it both preserves quality and extends shelf life. By effectively eliminating spoilage organisms and slowing down plant senescence, irradiation becomes a valuable addition to vacuum impregnation (VI) techniques. This combination serves the primary purpose of significantly prolonging the freshness and shelf life of various types of fresh produce. In a study by Yurttas et al. [89] mushroom slices underwent a process involving VI with 2 g/100 g ascorbic acid + 1 g/100 g calcium lactate at 50 mm Hg for 5 min and 5 min atmospheric restoration, followed by irradiation at 1 kGy using a 1.35-MeV e-beam accelerator. The control samples experienced structural deterioration during storage. Whereas the VI-irradiated samples maintained acceptable color and texture over storage time. Sensory evaluation consistently favored samples treated with VI and irradiation due to the inhibitory effect on spoilage microorganisms, reduction in microbial-induced browning, and extension of sliced mushroom shelf life by 15 days at 4 °C. Furthermore, Tong et al. [90] reported that VI (160 mm Hg) with a 4% (w/w) calcium lactate solution, combined with irradiation at 2 kGy using a 1.35-MeV e-beam accelerator, improved the textural properties of highbush blueberries by reducing softness. The treated fruits retained their quality parameters over the 14-day storage at 4 °C, whereas non-VI treated blueberries became soft and mushy.

10. Conclusion and future prospects

VI stands out as a versatile and promising technique in the realm of food preservation and processing, offering a multitude of benefits for enhancing product quality, extending shelf life, and conserving energy. Through VI, nutrients, bioactive compounds, and functional agents can be effectively infused into porous food matrices, leading to improved nutritional content, sensory attributes, and overall product stability. The unique hydrodynamic mechanisms (HDM) involved in VI, driven by pressure gradients, facilitate enhanced mass transfer and impregnation, making it particularly effective in combination with other preservation methods. VI's applications span a wide spectrum of food products, by strategically selecting impregnation solutions and parameters, VI can effectively reduce water activity, inhibit microbial growth, enhance antioxidant properties, and minimize textural changes, thus creating high-quality, minimally processed products. Furthermore, VI's synergistic effects with techniques like electron-beam irradiation, ultrasound-assisted treatments, high-pressure processing, and even freezing and drying methods, demonstrate its potential to revolutionize the preservation landscape.

However, comprehensive investigations are still necessary to fully exploit its distinctive properties and large-scale industrial operation applications. Moreover, in-depth studies into the underlying mechanisms of VI, including the interplay between hydrodynamic forces and food matrix properties, could provide invaluable insights into process optimization and innovation. Developing predictive mathematical models and simulations could aid in scaling up VI for industrial applications, ensuring reproducibility and efficiency on a larger scale. In essence, the continuous evolution of VI techniques holds significant promise for the future of food preservation and processing.

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B R Vinod: Writing – review & editing, Writing – original draft, Validation, Resources, Conceptualization, Visualization. **Ram Asrey:** Validation, Supervision, Writing – review & editing. **Shruti Sethi:** Writing – review & editing, Supervision. **M Menaka:** Writing – review & editing. **Nirmal Kumar Meena:** Writing – review & editing, Validation. **Gouthami Shivaswamy:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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