

## EFFECTS OF PROCESS PARAMETER VARIATION ON MASS GAIN DURING VACUUM IMPREGNATION OF APPLE SLICES

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### *EFECTELE VARIATIEI PARAMETRILOR DE PROCES ASUPRA ACUMULARII DE MASĂ LA IMPREGNAREA ÎN VID A RONDELELOR DE MĂR*

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#### **ABSTRACT**

*Vacuum impregnation is a minimal processing method with wide applicability in porous food products, and can be used both for the development of functional foods and for the production of fortified food products. The experimental research presented in this paper aimed to highlight the effects of process parameter variation on mass gain during the vacuum impregnation of apple slices, using an experimental vacuum impregnation system developed by INMA within a national research program. Water was used as the impregnation liquid in the demonstrative experiment. The process parameters monitored during vacuum impregnation were: the vacuum pressure inside the impregnation vessel, immersion depth, holding time at the set vacuum pressure, and internal pressure equilibration time. The experimental results showed that vacuum pressure (investigated range: 50–350 mbar) is the main factor influencing mass gain of the treated product, decisively affecting the efficiency of the impregnation process. In this context, the lower the vacuum pressure (in this case, 50 mbar), the greater the capacity of the product to incorporate physiologically active compounds, with a potential direct positive effect on product quality, nutrient content, and shelf life. The effect of vacuum pressure is further modulated by the holding time, particularly at short holding periods (120 s). It appears that extending the holding time does not necessarily improve impregnation efficiency, especially at low vacuum pressures.*

#### **REZUMAT**

*Impregnarea în vid este o metoda de procesare minimală cu aplicabilitate largă în randul produselor alimentare cu structură poroasă, putând fi utilizată atât pentru obținerea de produse alimentare funcționale cat și pentru obținerea de produse alimentare fortificate. Cercetarea experimentală prezentată în cadrul acestei lucrări și-a propus să pună în evidență efectele variației parametrilor de proces asupra acumulării de masă la impregnarea în vid a unor rondele de măr, utilizând un model experimental de instalatie de impregnare în vid, dezvoltat de INMA în cadrul unui program național de cercetare. Lichidul de impregnare utilizat pentru experimentul demonstrativ a fost apa. Parametrii urmariti în timpul procesului de impregnare în vid au fost: presiunea de vid din interiorul vasului de impregnare, adâncimea de imersare, timpul de menținere la presiunea de vid setată și timpul de echilibrare a presiunii interne. În urma efectuarii cercetărilor experimentale s-a constatat faptul că presiunea de vid (domeniu de observare: 50...350 mbar) este factorul principal care influențează acumularea de masă, asociat produsului tratat, influențând decisiv eficiența procesului de impregnare. În acest context, cu cat presiunea de vid este mai mică (în cazul nostru 50 mbar), cu atât produsul ar putea îngloba o cantitate mai mare de compusi fizio logic activi, cu potențial efect pozitiv direct asupra calității, conținutului de nutrienți și perioadei de valabilitate a produsului respectiv. Efectul presiunii de vid este modulat în continuare de timpul de menținere, în special la perioade scurte de menținere (120 s). Se pare că o perioadă extinsă de menținere nu va aduce neapărat beneficii procesului de impregnare, în special la presiuni de vid scăzute.*

#### **INTRODUCTION**

Fresh fruits and vegetables are an important source of essential vitamins and minerals, such as vitamin A, vitamin C and potassium, which are necessary for human nutrition (Gherghi, 1994; Hoffmann *et al.*, 2014; Palumbo *et al.*, 2022; Cirillo *et al.*, 2023). The attributes of fresh fruits and vegetables (appearance, texture, flavor and nutritional value) are traditional quality criteria, and food safety (chemical, toxicological and microbial) and traceability are becoming increasingly important for all actors along the supply chain, from farm

to consumers (*Mahajan et al.*, 2014; *Palumbo et al.*, 2022). As living products, fresh fruits and vegetables are metabolically active and highly perishable, requiring a coordinated action between growers, storage operators, processors and retailers to maintain quality and reduce food losses and waste (*Barth et al.*, 2009; *De Corato*, 2020). These products contain 80-90% water (*Khan et al.*, 2017), which favors microbial activity and enzymatic reactions inside cells, leading to chemical degradation and quality loss (*Berger et al.*, 2010; *Srisamran et al.*, 2020). Due to its highly perishable nature, this product category represents the food group with the second highest value of losses and waste across all stages of the supply chain (approximately 22%), being surpassed only by root crops, tubers and oilseeds (*SOFA*, 2019). Therefore, post-harvest treatments are essential to minimize microbial spoilage and reduce the risk of pathogen contamination for fresh fruits and vegetables. Preservation technologies aim to reduce the intensity of metabolic processes such as respiration and transpiration, as well as the activity of pathogenic microorganisms, which are the main cause of decomposition processes.

Traditional methods of preserving fresh produce negatively affect the sensory and nutritional characteristics (*Vinod et al.*, 2024). The increasing consumer preferences for quality foods have led to the significant development of various technologies in the food industry (*Ashitha and Prince*, 2018).

Consumers are increasingly demanding ready-to-use and ready-to-eat plant-based food products, of fresh quality and containing only natural ingredients, becoming increasingly informed and aware of the hygienic aspects of their lives and diets. Therefore, it has become essential for producers and processors of vegetables and fruits to comply with both technological and hygienic-sanitary requirements.

Minimal processing has emerged as a response to the needs of consumers who are increasingly demanding plant-based food products that retain their natural flavor, color, texture and contain fewer preservation additives. Minimal processing is defined as a tendency to replace classical thermal treatment processes with new, athermal ones, which involve the use of "milder" techniques. To define minimal processing, in the specialized literature, the notion of "invisible" processing is also used, in order to emphasize the specificity of these techniques, following the application of which food products are made that retain to a high extent the sensory and nutritional qualities (fresh-like). The concept of minimal fruit processing is associated with maintaining freshness by preserving the initial biological structure of plant tissues.

The expansion of minimally processed concepts has been reflected in new, renewed and improved products. This has led to the technological development of processes formulated and designed to obtain a greater diversity of minimally processed products. In this context, the fresh-cut food market has experienced significant growth, especially in developed countries, due to consumer demands for healthy and nutritious food products with a fresh appearance (*Ma et al.*, 2017; *Yilmaz and Bilek*, 2018).

The quality of fresh-cut fruits and vegetables is strongly affected by physiological changes such as enzymatic browning caused by tissue damage and high respiration rates, and by physical factors including mechanical damage and removal of the outer protection, which favors faster weight loss, shrinkage, loss of color and appearance, and shortening of shelf life (*Siddiqui et al.*, 2011; *Palumbo et al.*, 2022).

Therefore, innovative food processing technologies, such as immersion and vacuum impregnation techniques, are being investigated and implemented to sanitize, reduce enzymatic browning, improve texture, and utilize nutrients (vitamins, probiotics, minerals, organic acids, phenols, etc.) in the fortification of freshly cut fruits and vegetables, to preserve and improve the quality and extend the shelf life of these products (*Radziejewska-Kubzdela et al.*, 2014; *Ashitha and Prince*, 2018; *Escobedo-Avellaneda et al.*, 2018; *Chinnaswamy et al.*, 2020; *Joshi et al.*, 2020).

Immersion treatments consist of immersing the product followed by removing the excess solution. This method is used for whole, peeled, shredded and sliced products, as well as for perishable products, as it favors the dispersion of the solution, covering the maximum surface area of the product (*Martín-Diana et al.*, 2007). A major advantage of these immersion treatments is the removal of cell exudates, which can have a negative effect on the post-harvest quality of the products. Depending on the product treated, the variables of the immersion process that must be taken into account are: immersion time, frequency, composition of the dissolved substance, temperature and concentration of the solution. Numerous studies have addressed immersion treatments with calcium (Ca) salts to extend the shelf life of products. Enrichment with Ca has several advantages, such as: reducing microbial growth due to the decrease in water activity, improving texture, acceptability and preventing browning due to oxidation phenomena and the development of undesirable flavors in freshly cut foods (*Soliva-Fortuny and Martín-Belloso*, 2003; *Alzamora et al.*, 2005; *Mu et al.*, 2022; *Mola et al.* 2016; *Zhang et al.*, 2019).

Vacuum impregnation is a method by which gases and part of the native liquids of the treated product are removed from inside the pores and replaced with an impregnation solution containing physiologically active compounds (minerals, vitamins, probiotics, prebiotics, antimicrobials, enzymatic anti-browning agents, pH reducing agents, phenolic compounds, natural dyes, etc.), without affecting the structural integrity of the food matrix (*Fito et al. 1994*). The process is carried out in two stages, the first stage being the reduction of the pressure to a certain vacuum level to remove the gases inside the pores, the second stage consisting of restoring atmospheric pressure to fill the pores with the impregnation solution. The main theories underlying the description of the vacuum impregnation treatment process are represented by the hydrodynamic mechanism (HDM) and the deformation-relaxation phenomenon (DRP), where the decrease in pressure and the subsequent return to atmospheric pressure are the main driving forces (*Blanda et al., 2008*). The process is used for the enrichment of fruit and vegetable tissues intended either for the production of fresh-cut products (*Park et al., 2006*) or for the production of fruit snacks, if the respective products are then dehydrated or fried (*Moreira and Almohaimeed, 2018; Castagnini et al., 2015*).

Vacuum impregnation has a wide applicability in the processing of food products with a porous structure, and can be used both to obtain functional food products (with additional health benefits) and to obtain fortified food products (with a role in preventing or correcting nutritional deficiencies).

The experimental research presented in this paper aims to highlight the effects of process parameters variation on the mass gain during vacuum impregnation of apple slices, using an experimental model of a vacuum impregnation system. The research also aimed to be a functional test of the vacuum impregnation system, in order to evaluate the capability of obtaining the necessary vacuum and ensuring the tightness of the air working path in the system, as well as the automatic management of the process under real working conditions. The paper did not aim to evaluate the influence of the vacuum impregnation process on the quality, nutritional content or shelf life of the treated product, but focused more on the generic vacuum impregnation process and the identification of process parameters with a more pronounced influence on the mass gain obtained after the treatment. The experimental model of the Vacuum Impregnation Instalation – IIV, was developed by INMA within a national research program.

## MATERIAL AND METHODS

The experimental research was carried out using a quantity of 12 kg of Red Delicious apples, produced in Romania and purchased from a supermarket (fig. 1).



**Fig. 1 - Red Delicious variety apples used in the experimentation**

To characterize the batch of apples used in the experiment, a sample of 5 apples was selected for which the following characteristics were determined: mass of each apple in the sample, average mass per sample, standard deviation of mass per sample, maximum equatorial diameter of each apple in the sample, average diameter per sample, standard deviation of maximum equatorial diameter per sample, maximum height of each apple in the sample, average height per sample and standard deviation of maximum height per sample.

The fruits were subjected to an impregnation process using an experimental model of Vacuum Impregnation System, developed by INMA within a national research program (fig. 2).



Fig. 2 - Experimental model of vacuum impregnation system- IIIV

The system performs the modification of the composition of porous food products by removing air and part of the internal liquids, followed by their impregnation with physiologically active compounds, without affecting the structural integrity of the food matrix, in order to improve the quality, nutritional content and extend the shelf life of the products. The system is equipped with an atmospheric pressure sensor (measurement range: -1...3 bar) inside the impregnation vessel, two solenoid valves for controlling the air paths and a micro controller (Mitsubishi Electronic, Alpha2 type, 8 analog inputs 0-10 VDC with analog input range 0-500, 6 relay outputs), which allow the permanent monitoring and control of the process parameters. Depending on the solid:liquid ratio (between the mass of the solid sample and the volume of the impregnation liquid) usually chosen at a value of 1:10 or 1:5, the working capacity of the system is 4 or 8 kg of product (distributed equally on the 4 trays arranged vertically on the system rack) for a volume of impregnation liquid of 40 l.

To perform dimensional and mass measurements, the following measuring and control devices were used, the characteristics of which are presented in Table 1:

Table 1

Characteristics of the measuring and control devices

No.	Instrument / device	Measurement range	Measurement uncertainty / Tolerable error
1.	Digital caliper	0÷150 mm	0,007 mm
2.	KERN electronic scale	0÷6000 g	accuracy: 2 g

The main measurement and control devices are shown in Figure 3.



Fig. 3 - Measuring and control devices

The fruits were de-stemmed to remove the core and seeds, after which they were peeled and sliced (perpendicular to the axis of symmetry) into slices with a thickness between 8 and 12 mm. To characterize the batch of slices used in the experiment, a sample of 5 slices was selected for which the following characteristics were determined: the thickness of each slice in the sample, the average thickness per sample and the standard deviation of the thickness per sample.

The mass of a sample was 400 g, 100 g each (3 - 5 slices, depending on their size) on each of the 4 trays arranged vertically on the rack of the impregnation system. The impregnation liquid used was water.

The parameters monitored during the vacuum impregnation process were: the vacuum pressure inside the impregnation vessel, the holding time at the set vacuum pressure (a time needed for the gases and a part of the native liquids contained within the porous microstructure, to exit the product and to obtain an internal pressure equal to the external pressure around the product) and the time for balancing the internal pressure (from the porous microstructure) with the restored external pressure.

Vacuum pressure and holding time were variables whose target values were entered by the operator at the beginning of the impregnation process. During operation, the operator was responsible only for monitoring compliance with the preset parameters. Compliance with the balancing time was ensured as follows: the timer reading was recorded at the moment when restoration of atmospheric pressure was completed, after which a period equal to the prescribed balancing time was allowed to elapse. To determine the end of the process, the operator added the desired balancing time to the timer reading recorded at the completion of pressure restoration, thereby obtaining the final timer value at which the process was stopped.

During the impregnation process, the tray rack was fully immersed in the liquid, with the lid covering the upper tray positioned 10 mm below the free surface of the impregnation liquid. As each tray had a height of 80 mm and the trays were vertically arranged on the rack, the hydrostatic pressure exerted by the liquid column above each tray differed, increasing with tray depth. At a given vacuum pressure established in the air above the impregnation liquid, the total pressure acting at the tray level increased with immersion depth. The first tray, with the product placement surface located 90 mm below the liquid level in the vessel, was followed by subsequent trays positioned at additional depths of 80 mm increments. As the products floated to the top of each tray during immersion, their effective depths were 10 mm, 90 mm, 170 mm, and 250 mm, respectively. Considering that a height difference of 1 mm corresponds to a pressure difference of approximately 10 Pa, and that the trays were spaced 80 mm apart, the products on each tray were subjected to an additional hydrostatic pressure of approximately 800 Pa (8 mbar). Consequently, the total pressures acting on the products during vacuum impregnation were higher than the vacuum pressures set in the air above the liquid by approximately 1 mbar, 9 mbar, 17 mbar, and 25 mbar, respectively. As a result, during the holding period at the preset vacuum pressure, the total pressure acting on the products increased with tray depth, which may influence mass gain at the end of the vacuum impregnation process.

For the experiments, 3 vacuum pressure levels were chosen, namely 50 mbar absolute pressure (-950 mbar relative pressure), 200 mbar absolute pressure (-800 mbar relative pressure) and 350 mbar absolute pressure (-650 mbar relative pressure). The holding times at the set vacuum pressure were set at 120 s, 240 s and 360 s. Also, the times for balancing the internal pressure in the pores were set at the same values, namely 120 s, 240 s and 360 s. When restoring atmospheric pressure, a delayed regime was chosen, to allow the impregnation liquid to penetrate the pores of the food matrix more slowly. The alternative was to restore atmospheric pressure more abruptly, with possible negative effects on the impregnation capacity, due to the faster depletion of the driving force of the entire process with the rapid decrease of the pressure gradient. For this reason, it was opted for the cyclical restoration of atmospheric pressure, namely for a time of 3 s in the phase of absorption of air from the outside, followed by a time of another 3 s for the occlusion of the path, the work phases continuing repetitively until the pressure inside the impregnation vessel was balanced with the atmospheric pressure from the outside.

At the end of the process, the sealed lid of the impregnation vessel was opened and the tray rack was removed from the liquid and allowed to drain. The samples were then removed from the trays, starting with the upper tray and proceeding to the lower one. Each apple slice was gently blotted with hygroscopic paper to remove excess surface liquid. The samples from each tray were subsequently weighed, and the results were recorded for processing and comparison with the initial masses.

The mass gain ( $C_m$ ) in the impregnation process was determined using the following formula:

$$C_m = \frac{(M_f - M_i)}{M_i} \cdot 100 [\%] \quad (1)$$

where:  $M_f$  is the final mass of the sample, after impregnation;

$M_i$  – the initial mass of the sample, before impregnation.

To evaluate the influence of process parameters on mass gain, a multifactorial analysis of variance (ANOVA) was performed. Mass gain was considered the dependent variable, while four independent factors were analyzed: vacuum pressure (three levels), depth (four levels), holding time (three levels), and balancing time (three levels). The corresponding experimental design followed a  $3 \times 4 \times 3 \times 3$  factorial model, allowing the assessment of both the main effects of each factor and their interactions on mass gain. The statistical analysis was conducted using the free software Jamovi Desktop.

## RESULTS

Regarding the characterization of the batch of apples used, following the processing and interpretation of the experimental data, the results presented in Table 2 were obtained (Legend: Avg. – Average; St. Dev. –

Standard Deviation per sample; Max. Equat. Diameter - Maximum Equatorial Diameter; Max. Height – Maximum Height).

**Table 2**  
The characteristics of the apples used in the experimentation

No. crt.	Mass [g]	Avg. [g]	St. Dev. [%]	Max. Equat. Diameter [mm]	Avg. [g]	St. Dev. [%]	Max. Height [mm]	Avg. [mm]	St. Dev. [%]
1	186	180	17.94	80.19	79.03	3.23	51.65	62.14	6.61
2	176			80.87			67.08		
3	208			82.00			68.11		
4	166			78.34			60.38		
5	164			73.76			63.48		

The apples used in the experiment belonged to the 70–75 mm, 75–80 mm, and 80–85 mm size classes, Extra category, color group A, according to the classification specified in Commission Delegated Regulation (EU) 2023/2429 of 17 August 2023. The standard deviation of sample mass exhibited a relatively high value (17.49%), attributable to the inclusion of apples from three distinct size classes, with maximum equatorial diameters ranging overall between 70 mm and 85 mm; therefore, the observed mass variability is justified.

Aspects during the determination of the characteristics of the batch of apples used in the experiment are presented in Figure 4.



**Fig. 4 - Determination of the characteristics of the apples used in the experimentation**

Regarding the characterization of the batch of slices used, following the processing and interpretation of the experimental data, the results presented in Table 3 were obtained, the meaning of the abbreviated terms being similar to those presented in Table 2.

**Table 3**

Characteristics of the apple slices used in the experimentation

No.	Thickness [mm]	Avg. [mm]	St. Dev. [%]
1	8.52	10.31	1.16
2	11.44		
3	11.00		
4	9.85		
5	10.74		

Aspects during the determination of the characteristics of the batch of slices used in the experiment are presented in Figure 5.



**Fig. 5 - Determination of the characteristics of the apple slices used in the experimentation**

During the experiments, vacuum pressure, holding time, and balancing time were determined based on direct readings displayed by the system, using the indications provided by the pressure sensor and the software timer integrated into the process computer of the vacuum impregnation system.

Following initial interaction with the treated product, visual and tactile observations indicated that, at a vacuum pressure of 50 mbar, the product tended to exhibit a softer texture, with partial impairment of the food matrix structural integrity. Selected aspects of the experimental research are illustrated in Fig. 6.



Fig. 6 - Aspects during experimental research

A total of 108 samples were analyzed in accordance with the planned experimental design. The obtained results are presented in Fig. 7, where the abscissa represents the values of the independent factors and the ordinate represents the corresponding values of the dependent variable.

### INDEPENDENT FACTORS INFLUENCE ON MASS GAIN

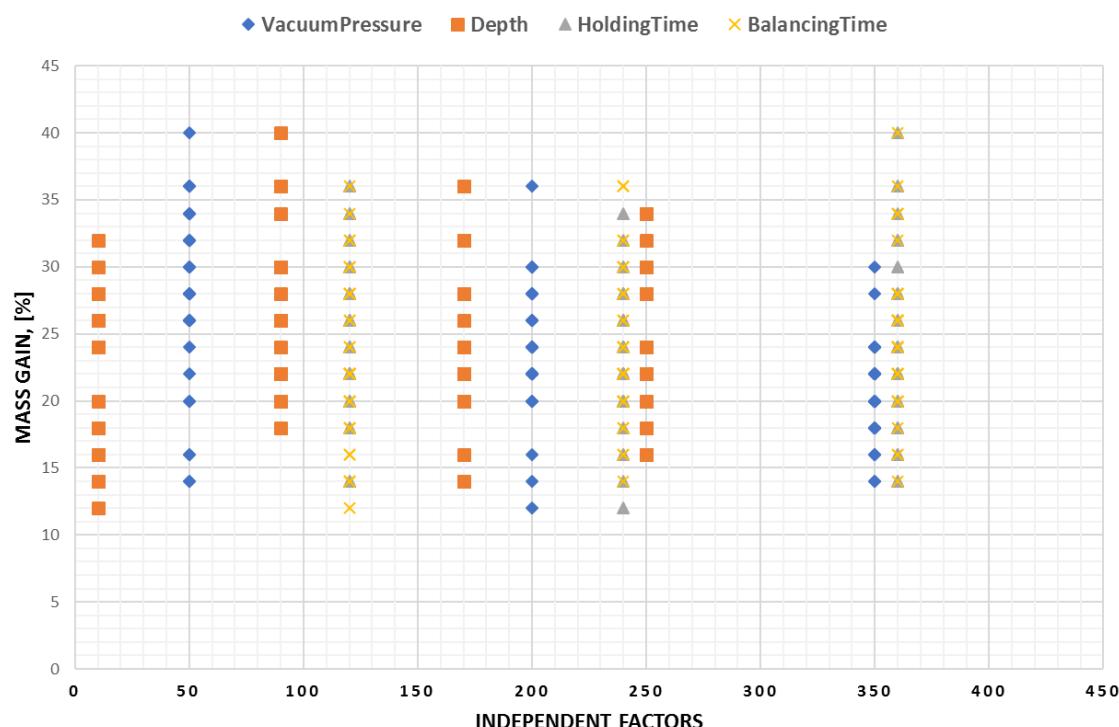


Fig. 7 - Experimental results

A multifactorial ANOVA was performed using Jamovi Desktop software to evaluate the effects of vacuum pressure (50, 200, and 350 mbar), depth (10, 90, 170, and 250 mm), holding time (120, 240, and 360 s), and balancing time (120, 240, and 360 s) on mass gain during the impregnation process. The results of the analysis are presented in Table 4.

The ANOVA analysis results

Table 4

#### ANOVA - MassGain

	Sum of Squares	df	Mean Square	F	p	$\eta^2 p$
Overall model	2234.9	35	63.9	3.41	< .001	

## ANOVA - MassGain

	Sum of Squares	df	Mean Square	F	p	$\eta^2 p$
VacuumPressure	970.7	2	485.3	25.93	< .001	0.419
Depth	121.3	3	40.4	2.16	0.100	0.083
HoldingTime	94.9	2	47.4	2.53	0.086	0.066
BalancingTime	72.0	2	36.0	1.92	0.154	0.051
VacuumPressure $\times$ HoldingTime	209.8	4	52.4	2.80	0.032	0.135
Depth $\times$ HoldingTime	218.9	6	36.5	1.95	0.084	0.140
VacuumPressure $\times$ BalancingTime	173.3	4	43.3	2.31	0.065	0.114
VacuumPressure $\times$ HoldingTime $\times$ BalancingTime	374.0	12	31.2	1.66	0.093	0.217
Residuals	1347.8	72	18.7			

**Main effects**

A significant main effect of vacuum pressure was observed,  $F(2, 72) = 25.93$ ,  $p < 0.001$ , partial  $\eta^2 = 0.419$ , indicating a large effect size. Lower vacuum pressure (50 mbar) resulted in significantly higher mass gain compared with higher pressure levels. Post-hoc Tukey comparisons (Table 5) confirmed that all pairwise differences among the three pressure levels were statistically significant ( $p < 0.01$ ).

**Table 5****Post-hoc Tukey test results for vacuum pressure**

Comparison							
VacuumPressure	VacuumPressure	Mean Difference	SE	df	t	p <sub>tukey</sub>	
50	- 200	4.00	1.02	72.0	3.92	< .001	
	- 350	7.33	1.02	72.0	7.19	< .001	
200	- 350	3.33	1.02	72.0	3.27	0.005	

The main effects of depth, holding time, and balancing time were not statistically significant ( $p > 0.05$ ). However, depth ( $p = 0.100$ ) and holding time ( $p = 0.086$ ) exhibited marginal trends toward significance.

**Interactions**

A significant interaction between vacuum pressure and holding time was observed,  $F(4, 72) = 2.80$ ,  $p \approx 0.032$ , partial  $\eta^2 = 0.135$ . This result suggests that the effect of vacuum pressure on mass gain depended on the duration of the holding time. At a holding time of 120 s, the differences among pressure levels were most pronounced, with 50 mbar yielding approximately 10 units higher mass gain than 350 mbar. In contrast, at longer holding times (240–360 s), the differences between 200 and 350 mbar diminished (Table 6).

**Table 6****Estimated marginal means for the Vacuum Pressure  $\times$  Holding Time interaction**

Holding time	Vacuum pressure	Mean mass gain	SE	95% Confidence Interval	
				Lower	Upper
120	50	30.7	1.25	28.2	33.2
	200	25.0	1.25	22.5	27.5
	350	20.3	1.25	17.8	22.8
240	50	27.0	1.25	24.5	29.5
	200	21.0	1.25	18.5	23.5
	350	21.2	1.25	18.7	23.7
360	50	26.0	1.25	23.5	28.5

Holding time	Vacuum pressure	Mean mass gain	SE	95% Confidence Interval	
				Lower	Upper
	200	25.7	1.25	23.2	28.2
	350	20.2	1.25	17.7	22.7

Other two-way interactions (vacuum pressure  $\times$  balancing time and depth  $\times$  holding time) approached statistical significance ( $0.06 < p < 0.09$ ), suggesting possible secondary modulatory effects; however, these interactions did not reach the conventional significance threshold ( $\alpha = 0.05$ ).

Higher-order interactions (3-way and 4-way) were not statistically significant.

## CONCLUSIONS

Vacuum impregnation demonstrates broad applicability in the processing of food products with porous structures and can be effectively used for the production of both functional foods, providing additional health benefits, and fortified foods aimed at preventing or correcting nutritional deficiencies.

Based on the experimental investigations, data processing, and statistical analysis, vacuum pressure was identified as the primary factor influencing mass gain of the treated product, thereby decisively affecting the efficiency of the impregnation process. Lower vacuum pressure values (50 mbar in the present study) resulted in higher mass gain, indicating an increased potential for incorporating physiologically active compounds, with possible direct positive effects on product quality, nutrient content, and shelf life.

The effect of vacuum pressure was further modulated by holding time, particularly at short holding periods (120 s). Extending the holding time did not necessarily enhance impregnation efficiency, especially at low vacuum pressure levels.

Depth and balancing time did not exhibit statistically significant effects under the investigated experimental conditions.

Although the present study did not specifically address changes in product quality resulting from the impregnation process, visual and tactile observations indicated that lower vacuum pressures led to a softer product texture. At 50 mbar, partial impairment of the food matrix structural integrity was observed. In the absence of texture-enhancing agents (e.g., calcium salts) in the impregnation solution, a balance must therefore be achieved between maximizing mass gain and preserving a natural product texture.

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