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RECENT INSIGHTS IN VACUUM IMPREGNATION APPLICATION ON MINIMAL PROCESSED FRUITS AND VEGETABLES

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Abstract

Recently, the consumer demand has increased in respect to minimally processed food, with health-promoting values and desirable sensory attributes. Fruit and vegetables are characterised by a multitude of health benefits, including their low calorie content, high dietary fibre content, and abundance of nutritional components, such as vitamins and minerals. They are considered essential components of a human diet. Vacuum impregnation (VI) combined with drying could be an interesting alternative to obtain a wide range of natural functional products. Vacuum impregnation is a technique that uses pressure gradients to incorporate functional active components into the structural matrix of porous fruits and vegetables without substantially modifying the organoleptic properties. Therefore, the aim of this study is to present the mechanism of action and recent application of vacuum impregnation in fruits and vegetables. The results show great functional properties of minimally processed fruits and vegetables following the application of vacuum impregnation technology.

Key words*: minimal processing, vacuum impregnation, functional properties, fruits, vegetables.*

INTRODUCTION

Vacuum impregnation is a valuable method which can be used to rapidly introduce different ingredients in concentrated solutions into food matrices in order to obtain food products with improved functional characteristics (Saleena et al., 2023; Gautam et al., 2024). This technology can also be used to fortify food by the impregnation of a solution rich in bioactive compounds and specific minerals which can enhance the nutritional quality of the product (Bernardino et al., 2021; Mierzwa et al., 2022). In addition to bioactive compounds, vacuum impregnation technique can introduce viable microbial cells into food products, like probiotic bacteria (Bernadino et al., 2021).

Impregnation of solutes is a specific process used to increase the composition of a certain compound or a combination of compounds in a food matrix to obtain a functional food product (Gonzalez-Perez et al., 2022). Plant tissues have a complex internal microstructure consisting of cells, intercellular spaces, pores, etc. The pores are covered with gas or natural liquid; due to their reasonably large size, pores allow beneficial microorganisms and physiologically active substances such as minerals and vitamins to accumulate on the surface of plants. It has been demonstrated in various studies that impregnation was carried out successfully under vacuum and atmospheric pressure conditions (Assis et al., 2019; de Medeiros et al., 2022; Elvan et al., 2022). Vacuum impregnation is a non-thermal and non-destructive treatment (Castagnini, J.M., 2021; Nishad et al., 2022; Vinod et al., 2024) that aims at modifying the food matrix through partially removing water or air and impregnating bioactive compounds without affecting the structural integrity of the materials. This technique leads to fill in the entire volumes of pores in fruit and vegetable tissues, therefore modifying sensory attributes and physicochemical properties of food products (Elvan et al., 2022).

During the application of vacuum impregnation process, the impregnation solution penetrates the intracellular spaces of food tissues, enhancing mass transfer efficiency. The advantages of using this technology to improve fruit and vegetables properties are short processing times, relatively low costs and the potential to be scaled up at industrial level (Durán-Castañeda et al., 2024).

The objective of this study was to present the latest findings on the application of vacuum impregnation technology for the functionalisation of minimally processed fruit and vegetables.

RESULTS AND DISCUSSIONS

It is well known that fresh fruits and vegetables represents a great source of essential minerals, vitamins, and antioxidants, having a great potential in improving human health. Traditional technologies and processing methods that are used for fruit and vegetable conservation affect in a negative way both nutritive and sensorial aspects of products (Vinod et al., 2024). To overcome these problems, in recent years, many different technologies were developed in order to maintain and improve food quality, one of these technologies being vacuum impregnation.

The vacuum impregnation process is comprised of two primary steps, namely (1) reducing pressure inside the system (under vacuum), removing the liquids and gases present in the product and expanding the pores until the mechanical equilibrium is achieved through pressure gradients; (2) restoring the atmospheric pressure, known as the relaxation phase, and using the opposite pressure gradient to ensure the pores are saturated with the external solution as the tissue relaxes, until a new equilibrium is reached (Palumbo et al., 2022). In this context, vacuum impregnation can be used to modify organoleptic properties of porous foods and improve their sensory attributes, texture, physicochemical properties, antioxidant properties and enhance their bioactive content (Radziejewska-Kubzdela et al., 2023; Durán-Castañeda et al., 2024).

Fruit and vegetables are excellent matrices for vacuum impregnation application due to their porous texture. A study conducted by González-Pérez et al. (2023) aimed to optimize β-carotene impregnation from carrot juice or fresh product in *Pachyrhizus erosus* using vacuum. The following parameters were used: temperature of 40°C and an absolute pressure of 51 mmHg. The results showed that increasing the concentration of the solution resulted in increased concentrations of solute, total carotenoids and total soluble solids.

Mierzwa et al. (2022) used a combination between vacuum impregnation and ultrasound technology for the improvement of the infusion of ascorbic acid in cranberries. The results showed increased content in ascorbic acid and higher antioxidant activity.

Nishad et al. (2022) aimed at functionalise ash gourd with citrus peel polyphenols by vacuum impregnation. The optimised parameters like 2.21 minutes blanching pre-treatment, 432.31 mbar vacuum pressure and a duration of treatment of 28.18 minutes led to an increase in total phenolic content and antioxidant activity by approximately 300%.

A study conducted by Ertek et al. (2023) investigated the effects of vacuum impregnation using encapsulated phenolic extracts (turmeric, cinnamon, pomegranate peel) on strawberry fruits. The results showed that the best encapsulation agent was T80, which exhibited superior stability and yielded a functional strawberry snack.

Duarte-Correa et al. (2020) investigated the production of fortified potato chips using vitamin E and C and calcium through vacuum impregnation. The results showed that the use of this technology led to an increased content of fortifiers, namely an average retention of 72% of vitamin E, 53% of vitamin C and 90% of calcium by applying microwave vacuum drying with a power density of $1.7Wg^{-1}$ and an absolute pressure of 4.0kPa.

The effect of convective drying of mango fruit impregnated with polyphenols extracted from grape residue flour by vacuum impregnation was studied by Batista de Medeiros et al. (2022). The results of their study showed increased drying rate, softer product and higher carotenoids retention in samples treated with ultrasound-assisted vacuum. Higher phenolic compounds were found in samples submitted to vacuum impregnation assisted by osmotic dehydration and increased ascorbic acid content was determined for samples impregnated using also osmosonication.

Vacuum impregnation technology was used by Tangjaidee et al. (2025) for the infusion of cherries with fermented green coffee bean extract. The results showed enhanced bioactive compounds content of the treated samples.

Nuñez et al. (2025) used vacuum impregnation in the development of a snack based on Granny Smith apples, enriched with hydrolysed collagen. The results showed that using this technology made the collagen bioaccessibility very high during *in vitro* digestion.

Tables 1 and 2 presents information related to recent studies regarding vacuum impregnation technology applied to fruits and vegetables and its effects on the obtained products.

Table 1. Effects of vacuum impregnation technology application on fruits

Fruit	Impregnating solution	Effect	Reference
Apple	Calcium	Increased calcium concentration in treated samples.	Assis et al. (2019)
	Calcium lactate and black carrot phenolics	Increased calcium content, total flavonoids, total phenolics, total anthocyanins and increased antioxidant capacities.	Yilmaz & Bilek (2018)
	L. rhamnosus encapsulated within double emulsions	Higher impregnation was obtained when vacuum treatment was applied for 20 min.	Flores-Andrade et al. (2017)
	Aqueous extract of *Hibiscus sabdariffa* calyces	The samples presented increased content of total soluble phenols and improved antioxidant and flavonoid activities.	Anaya-Esparza et al. (2024)
Jujube	Calcium chloride (1% w/w, $CaCl_2$) and pectin methylesterase (PME) (15 U/mL)	Following vacuum impregnation treatment, jujube quality was maintained. Compared to control samples, the VI treated ones presented lower water loss and higher content in soluble solids, ascorbic acid and firmness.	Zhang et al. (2019)
Apricots	Solutions of citric acid and sucrose Plant extracts like rosehip, roselle, and rhubarb	The results showed solid loss and water gain in all infused samples by vacuum impregnation. the procedure led to positive effects on terpenes in treated samples.	Demir & Alpaslan (2024)
Cranberry	Ascorbic acid solution	US-assisted vacuum impregnation led to higher content in ascorbic acid, reduced difference in colour and good antioxidant properties.	Mierzwa et al. (2022)
Avocado	Solution of 1% calcium lactate + 1% ascorbic acid Solution of 1% calcium lactate + 1% citric acid	Both treatments led to the reduction of weight and loss of firmness. The polyphenol oxidase activity was inhibited and browning was delayed. Furthermore, an extension of shelf life was observed, compared to control samples.	Guzmán-Armenteros et al. (2025)
Lulo fruit	Lulo fruit juice	Good availability of pores into fruits with close maturity index and good impregnation capacity of those pores.	Hinestroza-Córdoba et al. (2021)
Chokeberry	Apple-pear juice	Following vacuum impregnation, an increased content of bioactive compounds was determined.	Nawirska-Olszańska et al. (2020)

Table 2. Effects of vacuum impregnation technology application on vegetables

Vegetable	Impregnating solution	Effect	Reference
Pepper	Lactic acid solution	Increased acidification degree and reduction of pH.	Derossi et al. (2010)
Yam bean	Polyphenolic extract of mango seed	The results showed higher content of total soluble phenols, higher antioxidant activity and pH reduction.	González-Moya et al. (2025)
Celery root	Vegetable juice, such as celery stalks, kale and onion	Pre-treating celery root by vacuum impregnation led to increasing bioactive components in dried samples.	Kręcisz et al. (2023)
Lentils	Micronutrient solution based on iron and zinc	The results showed enhanced water diffusion rate and higher migration of nutrients. Also, the phytic acid was significantly reduced due to vacuum impregnation.	Sarkhel & Roy (2024)

Vegetable	Impregnating solution	Effect	Reference
Lotus root	Lactic acid fermentation suspension	The used suspension led to the inhibition of phenylalanine ammonia lyase, polyphenol oxidase and peroxidase activity, maintaining colour and texture of samples.	Zhang et al. (2022)
Sweet potato	Polyphenol extract solution	High polyphenol content identified in the treated samples and stability of texture and colour.	Abalos Dr et al. (2020)
Kohlrabi	Beetroot and onion juices	The vacuum impregnation process led to a reduction of lightness of tested samples, and increased values of hardness, dry matter, chewiness and water activity. Moreover, additional volatile organic compounds from onions and beetroot were determined in the samples.	Kręcisz et al. (2025a)
Courgette	Freshly squeezed onion and kale juices	Good effects on bioactive content were observed.	Kręcisz et al. (2021)
Broccoli	Beetroot juice	Higher polyphenolic content and antioxidant activity.	Kręcisz et al. (2025b)
Carrot	Solution of 0.5% ascorbic acid, 0.5% citric acid and 8% sucrose	Increased ascorbic acid content and polyphenolic compounds.	Radziejewska-Kubzdela et al. (2024)

CONCLUSIONS

Nowadays, there is a growing demand for minimally processed foods with enhanced specific functional properties. Due to this fact, several technologies were developed or improved in order to meet consumer demands. One of these technologies is vacuum impregnation, which is preferred because is non-thermal and non-destructive and is suitable for fruit and vegetable processing. This paper highlighted some of the recent insights on vacuum impregnation application on minimally processed fruits and vegetables. The studies reviewed indicated that products treated with this technology exhibited improved physicochemical quality and increased concentrations of bioactive constituents.

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