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Chapter

Instant Controlled Pressure-Drop DIC as a Strategic Technology for Different Types of Natural Functional Foods

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Abstract

The increasing demand for functional foods requires the design, simulation, and further optimization of preservation processes of food with the purpose of keeping as high as possible the functionality of food products. Many studies have shown that the high consumption of fruit and vegetables prevent chronic diseases such as obesity, type 2 diabetes mellitus, cancer, among others. Fruits and vegetables are important sources of nutrients, dietary fibers, and phytochemicals. However, after harvest, they are highly perishable because of their high moisture content of almost 3–9 g H_2O/g db. Solar and airflow drying processes have been the most popular methods to increase the shelf life of these products. Nevertheless, low organoleptic and nutritional quality, hygiene problems, and long drying periods constitute significant barriers to a more widespread use. "Swell-drying" is a special drying process convective airflow drying (CAD) to the instant controlled pressure-drop (DIC) expansion. This process is well-known as guaranteeing (1) the preservation of functional properties; (2) the organoleptic quality; (3) the effective microbiological/fungi decontamination; and (4) a reduced energy consumption and a lower drying time. DIC treatment is a high temperature/short time (HTST) process that improves both performance of drying process and high-quality functional foods.

Keywords: functional foods, swell-drying, instant controlled pressure-drop DIC, antioxidants, decontamination

1. Introduction

Although the term functional food is recently employed, the relation between health and the consumption of fruits, vegetables, and plant parts has been highlighted since ~2500 years ago by the Hippocratic phrase "Let food be thy medicine and medicine be thy food" [1].

The term "functional food" by itself was first used in the 1980s as "any food or ingredient that has a positive impact on an individual's health, physical performance, or state of mind, in addition to its nutritive value". Nowadays, this definition

remains appropriate, as long as such foods satisfy the three following conditions: (1) they are naturally rich in active ingredients, (2) they are able to be consumed as part of the daily diet, and (3) when they are ingested, they should enhance or regulate a particular biological process or mechanism to prevent or control a specific disease [2]. In this respect, many studies have shown that the consumption of fruits, vegetables, germinated seeds, and some parts of edible plants prevent some chronic diseases such as obesity, type 2 diabetes mellitus, hypertension, coronary heart disease, stroke, cancer, rheumatoid arthritis, eye diseases, among others [3–5]. They also show that fruit and vegetable consumers in most populations have half the risk of developing most types of cancer [5]. Fruit and vegetables are the most important sources of nutrients, dietary fiber, and phytochemicals. However, because of their high moisture content (up to more than 900% db), they are quickly perishable with a shelf life estimated to 2–3 days at the ambient temperature; this estimation greatly depends on the nature of material (without post-harvest processing). Hence, to increase their shelf life and subsequently maintain their functional properties, it is necessary to adopt accurate preservation techniques.

Nevertheless, many researches have shown that, despite the development of various preservation techniques, farmers over the world continue losing more than 40% of their products every year [6], while providing a decreased quality of functional foods.

The main unit operations of food preservation are drying, freezing, and canning. Dried materials are the most used foodstuffs because of: (1) their long shelf life once their water activity is so low that it inhibits chemical, microbial, and fungi (able to generate mycotoxin) activities, (2) their great convenience, and (3) the whole range of drying equipment and processes. However, although drying is the most common technique, its long-processing time at high temperature leads to a quality loss and high energy consumption [7–9].

There are many methods of drying, but sun drying is the most widely used methods throughout the developing countries of Asia, Africa, Central and South America [10]. However, the whole drying period can vary from 8 to 21 days according to the weather (solar radiation: temperature, relative humidity, and wind velocity) [10–13]. Another alternative method which uses the solar energy is called "the solar drying". This process differs from sun drying, by the use of equipment (solar dryers) that can control the direct solar radiation [14]. Through their simple use, sun and solar processes are differently weather dependent and commonly yield poor quality products. Shrinkage and texture compactness, loss of vitamins and bioactive compounds, and discoloration are elements of poor quality [12, 13, 15]. Besides, the dried products may be contaminated by dust, dirt, insects, birds, microorganisms, etc.

Since the eighteenth century, new drying methods such as convective airflow drying (CAD), spray drying, drum drying, lyophilization freeze drying (LFD), microwave drying (MWD), infrared drying (IRD), superheated steam drying (SSD), and some operations of puffing, pooping, or extrusion have been developed to improve conventional drying processes [16].

CAD is the most preservation technology applied for the fruits and vegetables at industrial level. It is known as the process where the heat used to evaporate the product's water is supplied by a stream of hot air [17]. In this process, the food product is exposed to a forced hot air flow at different levels of temperature, between 50 and 100°C, depending on the product's heat sensitivity, until final required moisture content is achieved. Despite its widespread application, this process is highly energy consuming at about 1 kW kg^{-1} of evaporated water. Moreover, the long exposure time to high temperature has a negative effect on color, nutritive value (vitamins, proteins, and fats), antioxidant activity (bioactive compounds), functional properties (rehydration response, water and oil holding capacities), texture, and shelf life.

Therefore, a main part of food engineering research has been devoted to improving the existing preservation techniques, or define innovative operations, to reduce the energy consumption, maintain the functional properties, and ensure the safety of products.

2. Fundamental approach of convective airflow drying CAD

The external driving force of CAD is the gradient of the vapor pressure between the surface of the product (exchange surface) and the surrounding environment. The rate of water evaporation from the product surface depends on the temperature and the water activity of this surface, while the rate of vapor removal from the product surface to the surrounding environment depends on the characteristics of the airflow: temperature (T_{AF}), velocity (v_{AF}), and relative humidity (HR). So, once the operation becomes adequately intensified by adequately increasing T_{AF} and v_{AF}, and reducing HR, the external transfer resistance becomes negligible. With these Negligible External Resistance (NER) conditions, the internal water diffusion controls the drying process with, as driving force, the gradient of water concentration within the matrix. The product temperature referred as the wet bulb temperature (T_{WB}) decreases by increasing the drying rate. Thus, the process intensification normally increases the quality.

2.1 Heat and mass transfer processes during drying

Vapor is generated at the exchange surface. It is worth noting that the relatively low value of the wet bulb temperature (T_{WB}) allows lower vapor pressure in the material matrix. The transfer of mass (water) within the product to the exchange surface occurs mainly on liquid phase [18, 19]. Thus, the two opposite flows of heat dQ/dt and water dm_v/dt occur with the gradients in temperature and vapor pressure, respectively, as the driving forces:

$$\dot{Q} = hA_{eff}(T_{AF} - T_{WB}) \tag{1}$$

$$\dot{m}_v = k_p \rho_v A_{eff} \frac{(p_{v,T} a_{w,s} - p_{v,a} HR)}{P_t} \tag{2}$$

where h is the coefficient of heat convection transfer expressed in W m^{-2} K^{-1} and k_p the mass transfer coefficient expressed m s^{-1}. The heat transferred from the exterior environment to the exchange surface is almost exclusively used for evaporation [20].

$$T_{WB} = T_{AF} - \frac{k_p \rho_v}{h} L \frac{(p_{v,T} a_{w,s} - p_{v,a} HR)}{P_t} \tag{3}$$

When the external conditions control the operation, the drying rate evolves generally with the temperature level and the water activity at the exchange surface, thus defining the vapor pressure $p_{wa} = p^{WT} a_{w,s}$.

After controlling the hot air characteristics and external transfers, the whole operation of drying is controlled by the internal transfers (Negligible External

Resistance (NER) conditions), the intensification could be performed by holding higher wet bulb temperature inside the product which is normally smaller than the external airflow temperature (T_{AF}). The higher the T_{WB} is the higher the water diffusivity. However, this T_{WB} should be limited in order to maintain the quality of the product (texture, color, form, flavor, nutritive value, etc.) (**Figure 1**).

The liquid water diffusion is the main mass transfer occurring within the matrix towards the exchange surface. The liquid water is transferred within the porous matrix by classic diffusion, capillarity, and osmoses throughout numerous cell walls, etc. The transfer of water from the inner tissue to the outside surface involves migration through the cells, the enveloping and porous tissue structure, and then through the outside boundary layers. There are three main potential pathways which water can follow while passing throughout the plant tissue: (a) the apoplastic transport pathway (cell wall pathway), which occurs outside the cell membranes (plasmalemma) and can be defined as water transport through cell walls and intercellular space between cells; (b) the symplastic transport pathway (symplast pathway), inside the plasmalemma, characterized by a sap transport from one cell directly into another cell through small channels (plasmodesmata); and (c) the transmembrane transport pathway (vacuolar pathway), which is defined as a water exchange route between the cell interior (cytoplasm and vacuole) and the cell exterior (cell wall and intercellular space) across the cell membrane [19, 22–24]. The whole process occurs when the product temperature is lower than the water boiling point. To simplify all these phenomena, the whole transfer can be expressed by similar-Fick diffusion law, with an effective diffusivity (D_{eff}) [25]. Thus, by adopting the formulation of Allaf (1982), it can be expressed as:

$$\frac{\rho_w}{\rho_s}\left(\overrightarrow{v_w} - \overrightarrow{v_s}\right) = -D_{eff}\vec{\nabla}\left(\frac{\rho_w}{\rho_s}\right) \tag{4}$$

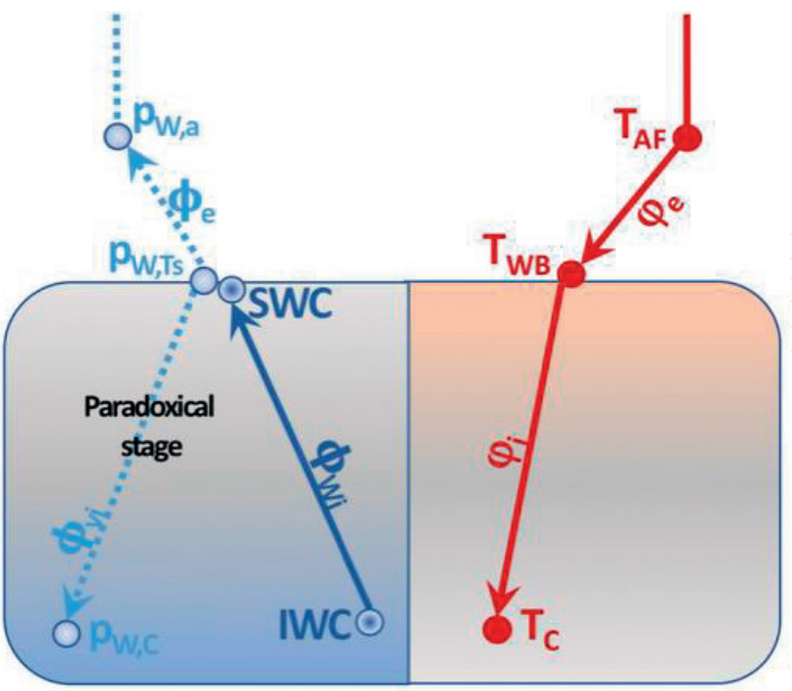


Figure 1.
Schematic representation of heat and mass transfers involved during airflow drying. Adapted from [21]. IWC: internal water content; SWC: superficial water content; $p_{W,a}$: vapor pressure in the air; $p_{W,Ts}$: vapor pressure at the surface; $p_{W,C}$: vapor pressure at the core; depending on temperature; Φ_{vi}: internal vapor flow; Φ_{ve}: external vapor flow; Φ_{wi}: internal water flow; T_{AF}: airflow temperature; j_e: external heat flow by convection; j_i: internal heat flow by conduction; T_{WB}: wet bulb temperature; T_C: core temperature.

where ρ_w and ρ_s are the apparent densities and v_w and v_s the average velocities of water w and solid s, respectively.

The part of the internal vapor transfer is frail and does not become relatively important before the final stage of drying. This internal vapor diffusion has a specific driving force of the gradient of vapor pressure, which is temperature dependent, while independent on water concentration. Hence, in many cases, the heat and vapor transfers within a porous matrix occur in specific coupled manners with an evaporation/condensation process [18]. The relationship between the temperature and the partial vapor pressure is the fundamental of the CAD paradoxical phenomenon [26].

The three steps of convective airflow drying (CAD) namely: (1) surface evaporation, (2) diffusion coupled with surface evaporation, and (3) paradoxical stage require distinct types of process intensification. Normally, the first intensification concerns an appropriate choice of the air temperature, speed, and relative humidity. These conditions must be managed to avoid both thermal degradation and case-hardening formation. Hence, after adequately increasing external transfers, internal transfer normally becomes the limiting process (NER condition). Subsequently, the expansion of the structure to improve the porosity allows increasing the water

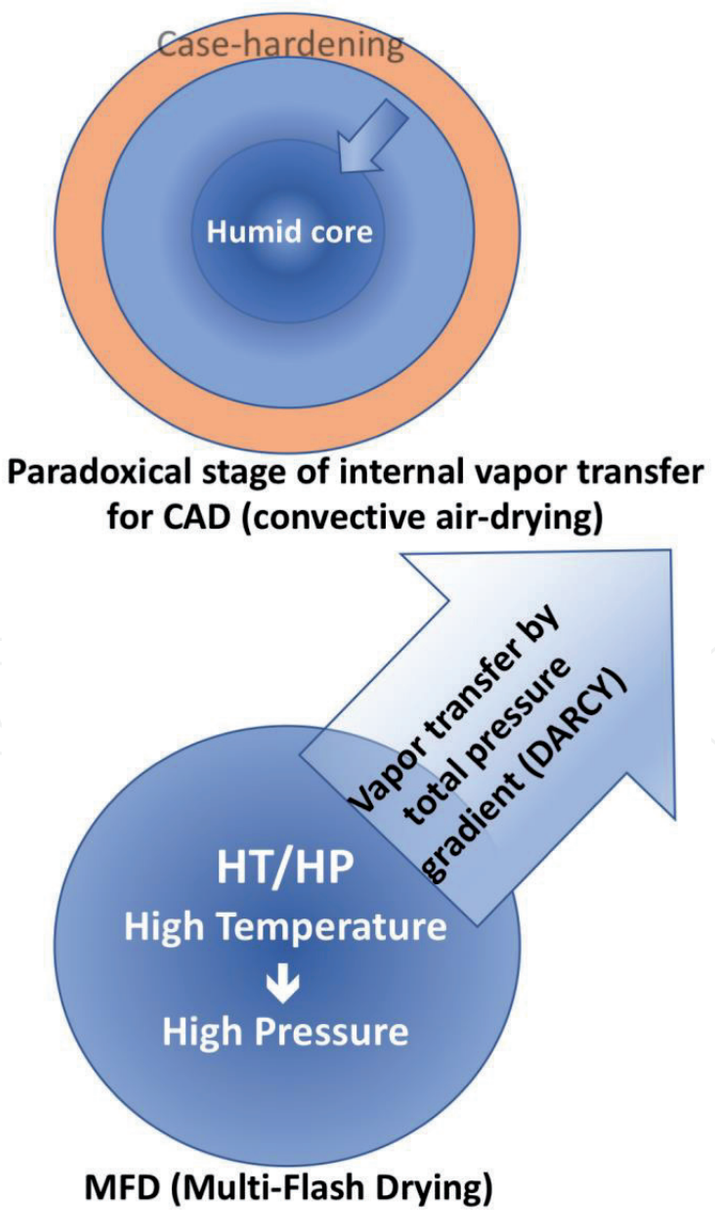


Figure 2.
Schematic description of the intensification of the paradoxical drying stage by MFA process [21].

diffusivity; thus, instant controlled pressure drop (well-known by its French acronym DIC: Détente Instantanée Contrôlée) becomes very interesting and even indispensable.

In the final stage of drying, the residual free or bound water, is merely transferred within the porous matrix as vapor. In the case of high-porous materials, the conductivity is weak with a significant paradoxical effect. To address this paradoxical situation and intensify the drying process, three solutions have been proposed: heating by microwave drying, drying by superheated steam, and drying by Multi-Flash Autovaporization (MFA) (**Figure 2**). In all these cases, Darcy's law can describe the main transfer phenomenon.

$$\rho_v V_v = -\frac{K}{\nu_v}\frac{\partial P}{\partial r} \tag{5}$$

where ρ_v is the vapor density, V_v is the average velocity of vapor, K is the permeability coefficient, and ν_v is the static diffusivity of vapor.

The MFA is defined as a drying process consisting in alternating cycles of high pressure and pressure drops over a relatively short time (typically between 20 and 200 ms), with a very high rate $>5 \times 10^5$ Pa s^{-1}. The cornerstone of this process is to generate a total pressure inside the product higher than at the surface, to avoid the paradoxical situation [27].

3. Instant controlled pressure drop (DIC) process in whole addressing drying issues

DIC is a thermo-mechanical process that consists of subjecting a product to high pressure saturated dry steam (almost between 100 and 1000 kPa according to the product and the objectives) for a short period of time (some seconds), followed by an abrupt pressure drop towards a vacuum (about 5 kPa). This abrupt pressure drops ($\Delta P/\Delta t > 0.5$ MPa/s) simultaneously triggers the autovaporization of the water (produced as a function of the temperature difference between the initial heat stage and the final equilibrium temperature), and swelling, with a possible rupture of cell walls and instant cooling of products, which stops thermal degradation (**Figure 3**). This process involves many perfectly controlled operating process parameters and intrinsic characteristics. They, respectively, are:

Operating process parameters: initial pressure and temperature, total pressure, vapor pressure, initial vacuum pressure, pressure drop rate, thermal processing time, temperature drop rate, volume ratio of the vacuum tank to the processing vessel, intrinsic density or filling ratio, quantity and apparent volume of the product to be processed, etc.

Intrinsic characteristics: shape/size of the raw material, water content, thermal conductivity, specific heat capacity, effective thermal diffusivity, effective mass diffusivity, rheological characteristics such as elasticity, viscosity, glass transition, etc.

Therefore, a wide range of possibilities for the selection and control of the treatment parameters allows optimizing one or more target characteristics in the product and/or the process. In the case of the intensification of airflow drying, to address the compactness of the product, the coupling of DIC expansion to airflow drying has been a solution, commonly known as the "Swell Drying" process (**Figure 6**).

The temperature and pressure levels during a DIC cycle are shown in **Figure 4**. First step: plant material is introduced in a processing reactor in which a vacuum

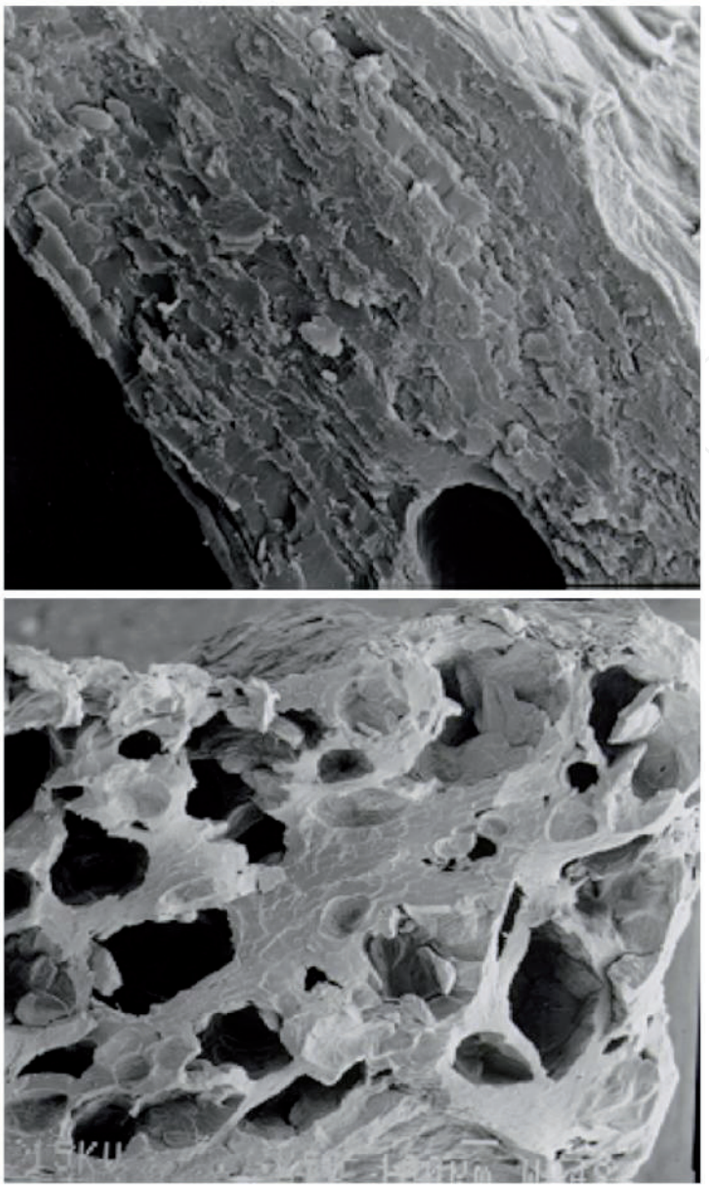


Figure 3.
Scanning electron micrographs of dried potatoes: standard airflow drying (left) and swell drying (right).

of around 4.5 kPa is established (**Figure 4a**). The initial vacuum is carried out to facilitate and mediate the close exchange between the incoming steam and the product surface. Second step: saturated steam is injected into the reactor at a fixed pressure level (from 0.1 up to 0.6 MPa) (**Figure 4b**). Heating transfer is performed mainly by steam condensation, which assures a very high coefficient of heat transfer. Once the levels of temperature and water content are almost homogenized in the material (needing some seconds) (**Figure 4c**), the sample is subjected to an instant controlled pressure-drop ($\Delta P/\Delta t > 0.5$ MPa s^{-1}) towards vacuum (**Figure 4d**); this is the third step of DIC. Fourth step: after a vacuum stage, the pressure is released towards the atmospheric pressure (**Figure 4e**) and the sample is recovered from the reactor [28]. Pressure and time operating parameters are selected according to the plant material.

The expansion of the product depends on the stress caused by the quantity of autovaporized water, the hydro-thermo-rheological (viscoelastic) behavior of the product, and the difference between the internal and external pressures. Thus, this operation is generally achieved when the moisture content results in the glass transition of the material [26].

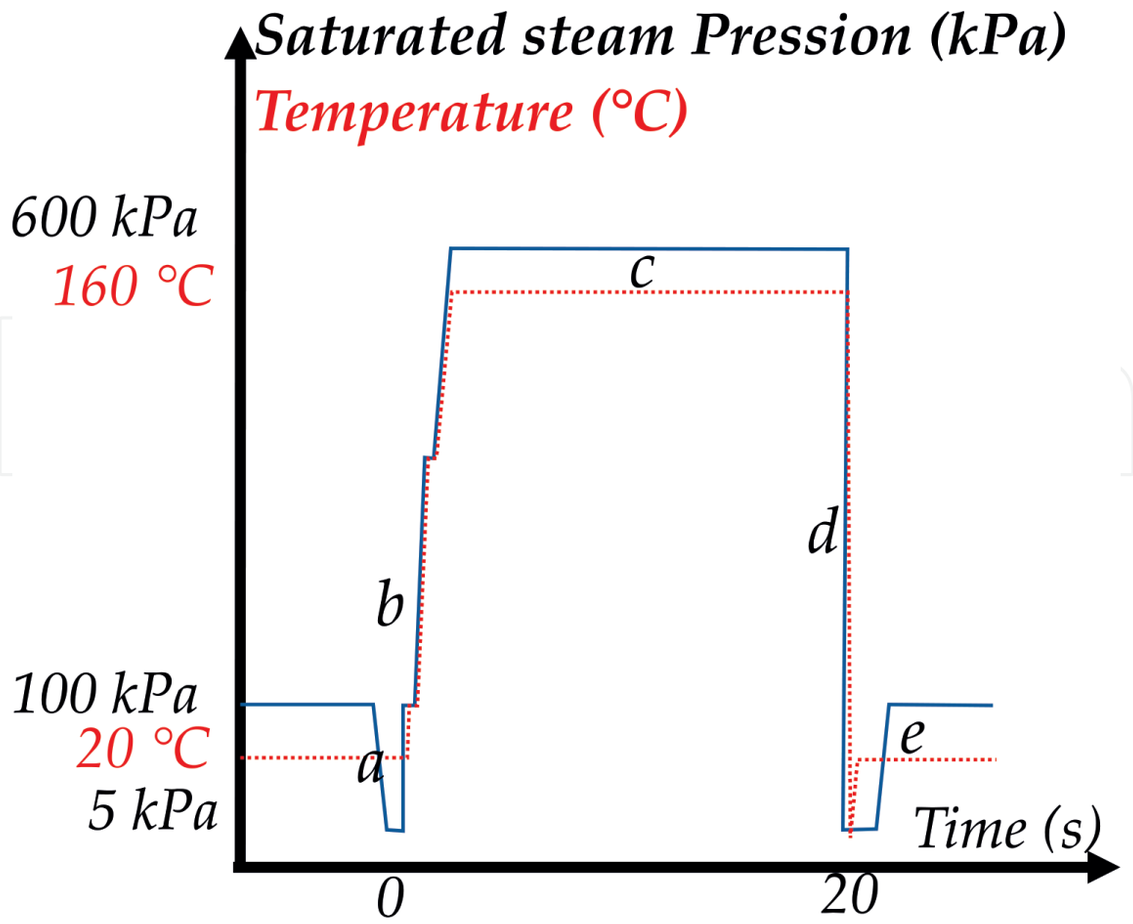


Figure 4.
Typical pressure-time profile for DIC processing cycle. (a): Establishment of an initial vacuum in the processing vessel; (b): injection of saturated dry steam at the selected pressure; (c) maintain of treatment pressure during selected time; (d): instant controlled pressure drop towards a vacuum; and (e): releasing to atmospheric pressure.

4. Applications of DIC as an innovative technology in manufacturing functional foods

In an age of convenient foods and pre-cooked meals, many consumers find that the high consumption of fruits and vegetables is difficult to achieve. For this reason, the production of high-quality dried fruit and vegetables becomes fundamental.

The DIC technology has shown very interesting results on the preservation of functional properties not exclusively in fruits and vegetables, but also on plants, germinated seeds, microalgae, among others foods. The DIC texturing usually makes it possible to increase availability and extractability of high-value biomolecules such as antioxidants. Moreover, the parameters of DIC treatment can be defined to achieve decontamination of bacteria, insects and larvae, fungi, etc., which is extremely important [29–31] mainly against the presence of aflatoxins. Hence, DIC products have a much longer lifetime, good consumer acceptance, and an excellent sensorial, hygienic, and nutritional quality. **Figure 5** shows some examples of swell dried fruits and vegetables snacks.

4.1 Swell-drying in increasing functional availability of active molecules

The generation of reactive oxygen species and other free radicals during metabolism is a necessary and normal process that ideally is compensated by an elaborate endogenous antioxidant system. However, the environment, lifestyle, and pathological situations provoke an excess of radicals, that when accumulate, results in oxidative stress that is related to chronic diseases [32]. Antioxidants have been defined as

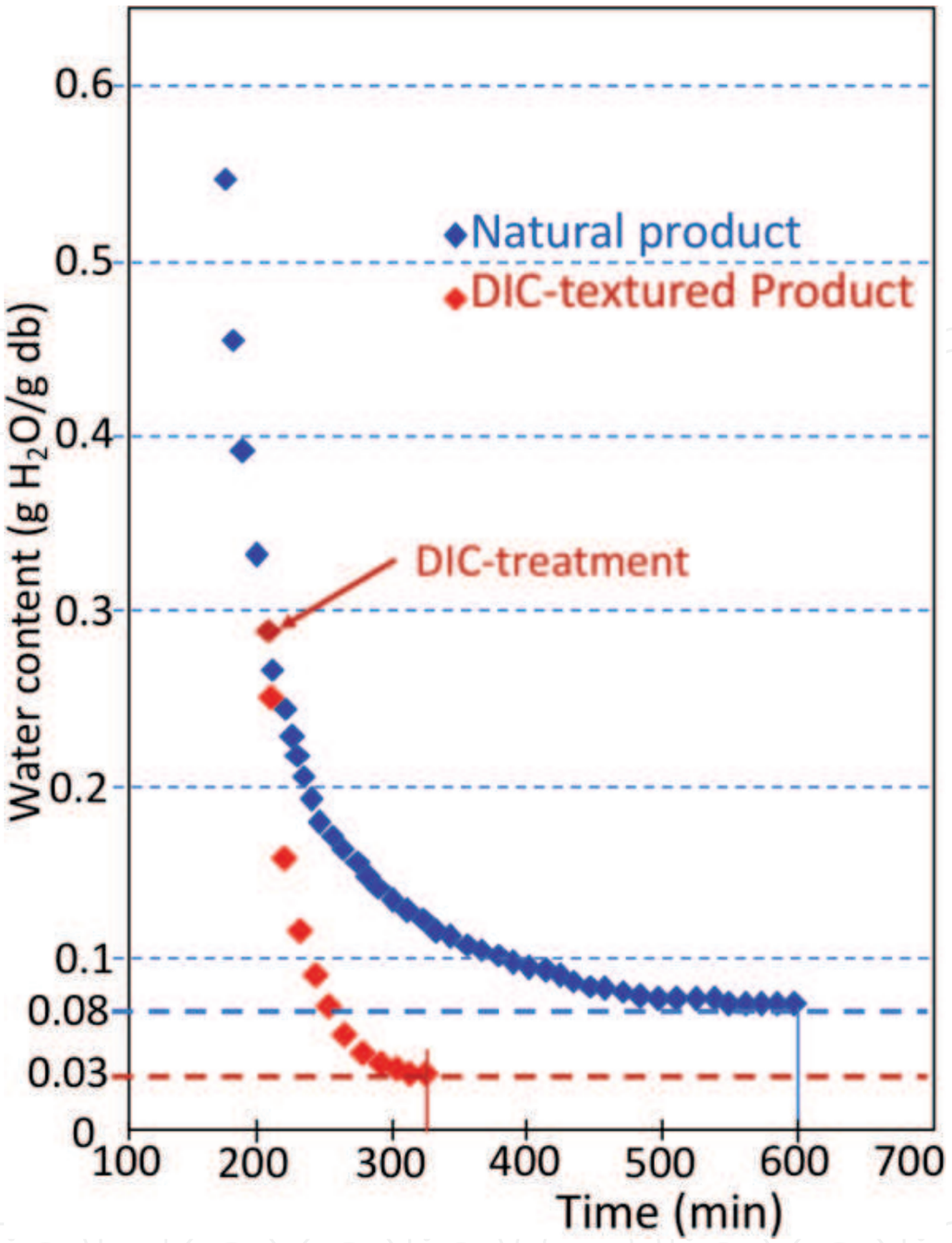


Figure 5.
Comparative study on CAD drying of conventional and DIC-textured apple samples.

any substance that when present at low concentrations compared with those of an oxidizable substrate, significantly delays or prevents oxidation of that substrate [33]. Therefore, during the past few decades, scientific studies have focused on the search of natural antioxidants sources and their preservation. The findings have shown significant evidence of the antioxidant effect on diseases prevention when consumers are feeding fruits and vegetables rather than individual antioxidants [32].

By DIC treating the partially dried material following an initial partially drying stage, the material becomes more porous and the tortuosity also increases. Water diffusivity usually increases, the final water content decreases, and drying time dramatically drops. Moreover, this implies a reduction of energy consumption compared with freeze-drying, but also with hot air drying. **Figure 6** shows the impact of DIC texturization on CAD kinetics of apples (**Figure 7**).

Respect to DIC treatment, various studies have shown that it has a direct positive impact on active molecules and their functional activity. Mounir et al., [30, 35]



Figure 6.
Swell-drying in manufacturing functional snacking [from www.abcar-dic.com].

studied the impact of DIC treatment on the onion and apple flavonoids and drying kinetics. Their results showed that in the case of apples, quercetin was the major flavonoid, followed by myricetin, kaempferol, and luteolin. And, in the onions, they were quercetin, myricetin, and kaempferol. Moreover, by measuring quercetin concentration before and after DIC treatment (0.3 MPa and 80 s), results showed that DIC apple samples reached up to 8 times more quercetin concentration compared to untreated samples. In the case of DIC onion samples, it was 31 times more. Additionally, the DIC texturing significantly improved the drying kinetics of both products. Drying time was reduced from 10 h (traditional airflow drying) to 5 h (swell-drying) in the case of apples, and from 11 h (traditional airflow drying) to 2.5 h (swell-drying) for onions.

Alonzo et al. [36] also studied the impact of airflow drying (HAD), freeze-drying (FD), and swell-drying (SD, DIC-assisted airflow drying) on the total phenol, total flavonoid, and total anthocyanin content of strawberries (*Fragaria var. Camarosa*). Their results showed that the optimum conditions of DIC to obtain the highest levels of phenols, flavonoids, and anthocyanins, as well as antioxidant activity were 0.35 MPa and 10 s. Moreover, there was no significant difference in total phenol and flavonoid content among FD and SD strawberry samples, which implies that DIC samples afford the same quality of freeze-drying at lower cost and in a shorter time. Additionally, the main anthocyanins in strawberries are pelargonidin-3-glucoside (Pe-3-Gl) and cyanidin-3-glucoside (Cy-3-Gl), and this study showed that the highest content of these anthocyanins was obtained after DIC treatment, being the saturated steam pressure parameter, the most important to be controlled. Additionally, by comparing the antioxidant capacity of HAD and FD to SD treated samples, antiradical activity (ARA) was determinate by using 2,2-diphenyl-1-picrylhydrazyl free radical (DPPH), showed that DIC increased by 9 and 10%, respectively, the antioxidant capacity of strawberries.

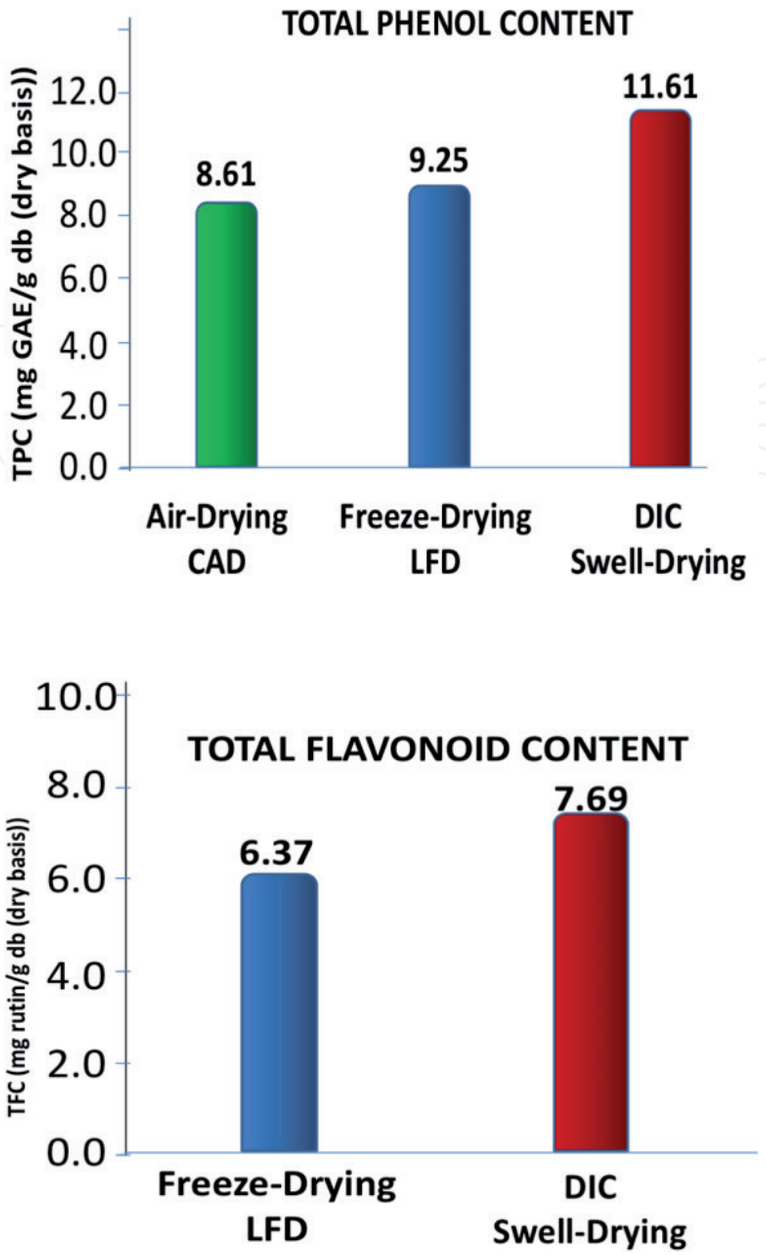


Figure 7.
Comparison of total phenol content (TPC) and total flavonoid content (TFC) of green pepper differently dried [34].

Amor and Allaf [37] also studied the effect of DIC treatment on the extraction of Roselle (*Hibiscus sabdariffa*) anthocyanins. Results showed that compared to water distillation (WD), DIC treatment improved both the kinetics and the yield of extraction of anthocyanins from Roselle calyces. Anthocyanins extraction time was reduced to one-third, from 10 min (WD) to 3 min (DIC). Moreover, DIC texturing improved the total monomeric anthocyanin [31] content of Roselle by up to 135%. TMA of raw material was of 8.96 mg/g db (dry basis), and TMA of DIC-treated samples was of 11.72 mg/g db. The main anthocyanins in the Roselle extract were Dp-3-sam (69–76%) followed by Cyn-3-sam (24–31%).

Téllez-Pérez et al. [34] evaluated the effects of drying and freezing couple to the DIC process on the phytochemical content and the antioxidant activity of Green Poblano Pepper (*Capsicum annuum, L.*). Traditional airflow drying (HAD), freeze drying (FD), and traditional freezing (TF) were studied as controls. Results showed that the total phenol content (TPC) varied widely according to different drying and freezing conditions. Compared to raw material (RM), both DIC and frozen samples

presented the highest content of TPC. Moreover, the total flavonoids content (TFC) of swell-dried pepper samples, which included a DIC texturing at (0.45 MPa for 40 s) showed the same performance as FD. In these two types of samples, TFC exhibited an increase of 1.20 times higher than RM. With respect to the antiradical activity (ARA) of peppers, swell-dried samples with DIC texturing at (P: 0.45 MPa, t: 40 s), FD and TF being, respectively, 1.05, 1.13, and 1.26 times higher than RM. Finally, by regarding the antioxidant capacity of the Trolox Equivalent Antioxidant Capacity assay (TEAC), results showed an increase in the antioxidant activity with respect to RM for HAD (1.36 times), FD (1.62 times), DIC couple to drying (1.69 times, P: 0.41 MPa, t: 54 s), and DIC coupled to freezing (2.89 times, P: 0.15 MPa, t: 40 s). DIC-assisted airflow drying and DIC-assisted freezing allowed both increasing of the availability of bioactive compounds while enhancing the antioxidant activity of peppers.

Santiago-Mora et al. [38] also evaluated the impact of freeze-drying (FD) and instant controlled pressure drop (DIC) on bioactive compounds and antioxidant capacity of berrycacti (*Myrtillocactus geometrizans*), a fruit of a perennial Cactaceae plant native to Central Mexico. Berrycacti is considered as functional food thanks to its antioxidant capacity. Then, its drying efficacy, phenols, non-extractable polyphenols, tannins, betalains, color, and antioxidant capacity were determined. Results showed that both freeze-dried and swell-dried samples showed the highest in-vitro antioxidant capacity compared to the fresh fruit. After both drying treatments, the results showed an increase of non-extractable polyphenols and condensed tannins; moreover, both had a good retention of betalains and ascorbic acid. In fact, both freeze-dried and DIC swell-dried samples exhibited effective preservation of antioxidant properties and retention of bioactive compounds, while DIC was greatly preserving color parameters and being the most cost-effective technology.

Sahyoun et al. [39] studied the impact of blanching, freezing/thawing, steaming, and DIC as pretreatment methods for carrots drying. Traditional airflow drying was employed as a control. And to evaluate the performance of each treatment on the functional properties of dried carrots, phospholipids, diacyl-glycerols, provitamin A, and carotene content were measured. Results showed that compared to the control, both freezing/thawing and DIC pretreatment coupled to vacuum drying preserve better the lipid content of dried carrots. Moreover, DIC samples showed thrice concentration of carotene compared to control.

Melki et al. [40] also studied the impact of DIC treatment on vitamins A, B1, B3, and B8 of fenugreek (*Trigonella-foenum-graecum*) and carob *(Ceratonia siliqua)* germinated seeds. As germination promotes the increase of biogenic compounds of seeds, DIC was applied to ensure its preservation. In the case of fenugreek germinated seeds, results showed that DIC increased vitamin B1, B3, and B8 content; and slightly decreased the vitamin A concentration. In the case of carob germinated seeds, results showed that DIC increased the vitamin A content by 82.54%, and slightly decreased B vitamins. In both cases, DIC allowed to increase the bioavailability of the vitamins, thanks to the cellular expansion, and allowed the decontamination of germinated seeds. Moreover, for both materials, the best DIC treatment conditions to guarantee cellular expansion and decontamination of seeds were found under 0.4 MPa steaming pressure for 30 s.

Namir et al. [41] also examined the effect of DIC texturing on the bioactive compounds and functional properties of cactus pear peel (*Opuntia ficus-indica*). Results showed that by comparing to traditional airflow drying, DIC treatment allowed more availability of phenolic compounds and β-carotene by 83 and 551%, respectively. Moreover, by using the 1,1-diphenyl-2-picrylhydrazyl ($DPPH^{\cdot}$) radical scavenging test, it was observed that the antioxidant activity of DIC-treated

peels was increased up to 53%. The best treatment conditions were defined under 0.6 MPa of steaming pressure for 15 s.

Allaf et al. [42] evaluated the impact of DIC technology in the sequential extraction of orange peel essential oil and antioxidants. Results showed that DIC technology enabled both essential oil extraction and matrix expansion, which improved solvent extraction of antioxidants. While orange peel essential oils (EO) extraction by hydrodistillation (HD) was achieved in 4 h to obtain a yield of 1.97 mg/g db, DIC-treated samples (after optimization) only 2 min were necessary to obtain a yield of 16.57 mg/g db. On the other hand, the solid residue was recovered to extract antioxidant compounds (naringin and hesperidin) by coupling DIC technology to solvent extraction (SE) and ultrasound UAE. Obtained results showed that by combining DIC and UAE, it was possible to enhance kinetics and yields of antioxidant extraction. Indeed, DIC/UAE results in 1 h extraction of 0.8 ± 1.6 g/g db of hesperidin and 6.45102 ± 2.3104 g/g db for naringin compared to 0.64 ± 2.7102 g/g db and 5.7 ± 1.6 g/g db, respectively, with conventional solvent extraction SE.

Mkaouar et al. [43] also studied the effect of DIC on the kinetics extraction of olive leaves (*Olea europaea* L.) polyphenols. Results showed that DIC-assisted solvent extraction allowed reducing the extraction time from 120 to 15 min while increasing the extracted yields. Furthermore, the ultra-performance liquid chromatography (UPLC) allowed following the extraction kinetics of the main phenolic compounds of olive leaves: apigenin-7-glucoside, hydroxytyrosol, luteolin-7-glucoside, oleuropein, tyrosol, vanillic acid, and verbascoside. And in almost all the cases, the extracted quantities were more important for DIC-textured olive leaves than untreated ones, with the exception of vanillic acid, which remained almost the same. Oleuropein was the major phenolic compound of olive leaves, reaching a maximum concentration of 84.9 mg/g dry matter after DIC texturization.

Berka-Zougali et al. also improved the extraction kinetics of natural antioxidants of myrtle (*Myrtus communis* L.) and buckthorn (*Rhamnus alaternus* L.) leaves through DIC [28, 44, 45]. For myrtle leaves, by comparing with untreated samples, DIC texturing clearly enhanced the extraction kinetics of both anthocyanins and flavonoids. In the case of anthocyanins, after 2.6 h of solvent extraction, DIC-treated leaves showed the same yield as untreated samples after 24 h. And in the case of flavonoids, after only 14 min, DIC-treated leaves showed the same yield as untreated samples after 112 min. Moreover, the antioxidant activity of myrtle leaves extracts was 3.57 times higher than one of the most common food preservatives, butylhydroxytoluene (BHT). In the case of buckthorn leaves, the extraction kinetics of phenols and flavonoids, and the antioxidant activity of both the dried leaves and the extracts were studied. Results showed that in only 3 min, DIC buckthorn leaves achieved the same yield of flavonol aglycones as untreated samples after 150 min. Aglycones are very important since they seem to be having a great therapeutic potential. Furthermore, the antioxidant activity of DIC buckthorn leaves was 68 times higher than BHT.

Many other reports have also shown that DIC technology induces modifications on the microstructure of food materials, which improves not only the availability of bioactive compounds but also it allows to reduce anti-nutritional and allergic factors.

4.2 Swell-drying to reduce anti-nutritional and allergic factors of foodstuffs

Legumes, as peas, chickpeas, lentils, beans, among others, are an important source of food proteins. They contain high amounts of essential amino acids, and they are a rich source of dietary fiber, minerals and vitamins [46]. Moreover, numerous studies suggest that consumption of legumes may have potential health

benefits as reducing the risk of cardiovascular disease [47], cancer [48], diabetes [49], hypertension [50], among others. Even though legumes provide health benefits, however, the possible presence of anti-nutritional factors (ANF) as phytates, trypsin inhibitors and oligosaccharides, causes some undesirable physiological reactions such as flatulence, low digestibility, and inhibition of vitamins absorption [51, 52]. ANF are defined as compounds which reduce the nutrient utilization and/or food intake of plants or plant products used as human foods or animal feeds [53]. For example, IgE-binding proteins have been also identified in majority on legumes, they can cause allergic response from mild skin reactions to life-threatening anaphylactic reaction [54].

Hence, to reduce or even eliminate the anti-nutritional and allergic legumes factors various treatments such as fermentation, precipitation, washing and filtration, heating, among others have been applied [51]. Among all these treatments, heating is the most commonly used [51, 54]. However, the final nutritional value of vegetables can be damaged by high-intensity heating. In this sense, the effect of DIC as a high temperature/short time (HTST) treatment has been evaluated in the case of some legumes on the ANF and allergic factors, achieving good results.

4.3 Effect of DIC on anti-nutritional factors

The effect of DIC on anti-nutritional factors has been studied on trypsin inhibitors of soybean seeds (*Glycine max*), and on phytates of lupin seeds (*Lupinus albus* and *Lupinus mutabilis*). Trypsin inhibitors (TIs) are the most important ANF of soybean seeds because they strongly inhibit the activity of key pancreatic enzymes trypsin and chymotrypsin, thereby they reduce digestion and absorption of dietary, even in the presence of high amounts of digestive enzymes [55]. To evaluate the effect of DIC treatment on TIs, Haddad et al. [51] submitted soybeans seeds with an initial trypsin inhibitor content of 41.6 IU/mg to different hydro-thermo-mechanical treatments varying three operating parameters: steam pressure (P) between 0.3 and 0.7 MPa, treatment time (t) between 20 and 60 s, and initial water content (W) between 30 and 50 g water/100 dry matter. Results showed that according to applied operating parameters, DIC treatment could achieve different reduction ratio of TIs, being remarked that the higher the pressure, the lower the TIs content. The best conditions to reduce TIs to a 94% were P = 0.7 MPa, t = 60 s, and W = 50 g water/100 dry matter. Heating causes the partial denaturation of proteins and generally gradually diminishing trypsin inhibitor levels in a time-temperature dependent mode [55]. Then, DIC as a very short hydro-thermo-mechanical treatment becomes an interesting technology to reduce the TIs content of soybeans seeds at industrial level.

Phytic acid or inositolhexa-phosphoric acid (IHP) is one of the most common heat resistant ANF in plants. IHP chelates micronutrient and reduce its bioavailability for monogastric animals, including humans, this, because the lack of phytase enzyme in their digestive tract. To reduce the phytic acid content in food, several pre-treatment methods such as soaking, germination, enzymatic treatment, and heating have been developed [56]. In the case of heating, according to some studies, to reduce the phytate content by 10%, it is necessary a thermal treatment of 30 min [57, 58]. Then, to evaluate the performance of DIC on the reduction of IHP content, lupin seeds were studied by Haddad et al., [52]. *Lupinus albus* and *Lupinus mutabilis* seeds with an initial IHP content of 18.36 and 23.54 mg/g dry matter, respectively, were cracked, dehulled, and moistened before DIC treatment. Evaluated DIC operating parameters were: steam pressure (P) between 0.4 and 0.7 MPa, treatment time (t) between 40 and 60 s, and initial water content (W) between 0.30 and 0.50 g H_2O/g db. Results showed that DIC treatment could reduce the total phytate

content by 16% (*L. albus*) and 19% (*L. mutabilis*) in only 60 s. Moreover, the decrease in total phytate content rises to 55% (*L. albus*) and 60% (*L. mutabilis*) for a 7 min treatment. For both varieties of lupin seeds, the best conditions to reduce IHP were P = 0.7 MPa, t = 60 s, and W = 0.50 g H_2O/g db.

4.4 Effect of DIC on allergic factors

Food allergies are adverse reactions to an otherwise harmless food, that occur when the immune system reacts to one or more proteins present in food that are recognized as foreign [54]. Legumes are essential constituents of human diets, contributing to both dietary protein and processed vegetable oil for human consumption. However, they are also an important source of food allergens such as 2S albumin, 11S legumin-type globulins, and the 7S vicilin-type [59]. Various studies have demonstrated that thermal processing as autoclaving, canning, steaming, among others can reduce, eliminate, or even enhance the allergenicity of legumes [60]. Thus, for each kind of thermal processing as well as for each legume, it is highly important to define the optimal heating conditions to eliminate or at least reduce the allergic factors. In the case of DIC technology, promising results have been found to reduce the legumes allergens [61–63].

Guillamón et al. [62] studied the effect of DIC treatment on Lupin (*Lupinus albus* var. Multolupa) in vitro allergenicity. Lupin cotyledons with an initial water content of 0.101 g H_2O/g db matter, were subjected to five different DIC treatments: DIC 1 (P = 0.3 MPa for 1 min), DIC 2 (P = 0.6 MPa for 1 min), DIC 3 (P = 0.45 MPa for 2 min), DIC 4 (P = 0.3 MPa for 3 min), and DIC 5 (P = 0.6 MPa for 3 min). To evaluate the impact of DIC on Lupins allergens, the IgE immunoreactivity of raw and DIC-treated extracts was evaluated by Western blot using a serum pool from 19 sensitized patients. Results showed that after DIC treatment, a reduction in the total IgE-reactive bands could be achieved. In fact, under DIC 5 treatment no IgE-immunoreactive band was found in soluble or insoluble protein fractions. According to the results, lupin allergens are relatively heat stable, and to eliminate their allergenic potency a combination of heat and pressure is required. A similar result was found by Álvarez et al. [64], who submitted lupins to an autoclaving treatment at 0.26 MPa for 30 min. At this respect, compared to autoclaving, DIC become an advantageous technology due to the reduction of time and energy.

Cuadrado et al. [63] researched the impact of DIC treatment on raw and roasted peanuts (*Arachis hypogaea*), lentils (*Lens culinaris*), chickpeas (*Cicer arietinum*), and soybeans (*Glycine max*) IgE antibody reactivity. Legume seeds with a constant initial water content of 50 g of water/100 g of dry matter were submitted to four DIC treatments: treatment A (P = 0.3 MPa for 1 min), treatment B (P = 0.3 MPa for 3 min), treatment C (P = 0.6 MPa for 1 min), and treatment D (P = 0.6 MPa for 3 min). To evaluate the impact of DIC on the studied legumes allergens, SDS-PAGE and immunoblotting analysis were applied.

In the case of peanuts, results showed that raw, roasted, and DIC-treated A and B peanuts presented no changes in the SDS-PAGE protein band pattern and minimal changes (decrease/increase) in the immunoreactive band pattern. Contrary, for DIC treatments C and D, a decrease in the band intensity in the range 15–65 kDa was observed, being more marked in roasted peanuts. On the other hand, in the case of lentils, chickpeas, and soybeans, all DIC treatments presented an important reduction of the major allergens and other minor immunoreactive proteins. Moreover, in the specific case of soybeans, under DIC treatment D almost all immunoreactive proteins were eliminated. According to the authors, significant alterations in protein structure may occur during heat treatment, and the nature and extent of which depend on the temperature and duration of the thermal processing.

Particularly, DIC treatment was able to produce an important decrease in the overall immunoreactivity of peanut, lentil, and chickpea extracts and a marked reduction in IgE recognition of soybean protein extract.

4.5 Swell-drying: a technology for food products decontamination

Even though, there is evidence that functional foods can play an important role in disease prevention and/or health promotion, guarantee the safety and quality of these products are very important aspects prior its commercialization and further utilization. Millions of cases of food-borne illnesses occur annually in the world, which ranging from mild aggravations to life-threatening situations. In general, food-borne illnesses are caused by the consumption of contaminated food by bacteria, viruses, or parasites, and symptoms as vomiting, diarrhea, and nausea typically last for 2–3 days. However, some patients can develop severe complications as hospitalization due to sepsis, stillbirths, hemolytic uremic syndrome, nerve paralysis, or even death [65]. Therefore, the complete elimination of pathogens from functional foods, without damaging its functional biomolecules, is imperative.

Decontamination has been defined as the elimination or reduction of microorganism's level. In general, foodstuffs decontamination methods can be divided into three categories: (a) thermal methods such as pasteurization, microwave, radio-frequency, infrared heating, among others; (b) chemical decontamination methods with chlorine dioxide, ozone, electrolyzed oxidizing water, organic acids, and dense phase CO_2, and (c) non-thermal decontamination methods such as high hydrostatic pressure, irradiation, pulsed electric fields, power ultrasound, and non-thermal plasma [66]. Among these methods, DIC showed satisfactory results on the decontamination of heat-sensitive and powders food products.

Setyopratomo et al. [31] studied the impact of DIC treatment on dehydration kinetics, product physical properties (water and oil holding capacity), and microbial decontamination of Cassava (*Manihot esculenta*) flour. Also, Mounir et al. [30] and Albitar et al. [29] evaluated the impact of DIC treatment on the decontamination of onions. Fresh Syrian white onions were peeled, washed, and cut into 50 mm length and d_p = 5 mm. For control, fresh onion slices were hot-air dried until final dehydration. For DIC-treated samples, onion slices were pre-dried until a moisture content of 0.3 g H_2O/g db. Pre-dried samples were submitted to DIC treatment following a two-variable central composite rotatable experimental design. Studied DIC operating parameters were: "P" = 0.20–0.5 MPa and "t" = 5 and 15 s. To evaluate the decontamination rate, total count plate method was used. Decontamination rate was expressed by log **F** of total microorganism content. Results showed that, under the selected operating conditions of DIC, the ratio log *F* ranged between 1.7 and 3.9. According to the statistical analysis, the higher the steam pressure "P", the higher the log *F* rate reduction of microorganism. Under 0.35 MPa and 15 s, DIC treatment allowed the total microorganism content to reduce from 875,000 germs/g (fresh onions) to 100 germs/g.

Debs-Louka et al. [67] evaluated the impact of DIC on the microbial destruction of *Bacillus stearothermophilus* spores. Results showed that DIC treatment enhance the spore destruction (**Figure 8**), giving a $D_{121.1°C}$ = 2.6 min and a thermo-resistance z of 7.6°C, instead of 4.2 min and 8.8°C, respectively [68]. Thermo-mechanical effect of DIC treatment leads the explosion of microorganism cells (vegetative or spores forms). Then, the higher the amount of generated steam within the cell and the smaller the pressure drop time, the more efficient the decontamination.

Finally, even if the correct selection of DIC operating conditions, steam pressure and treatment time have performed good results to decontaminate food products,

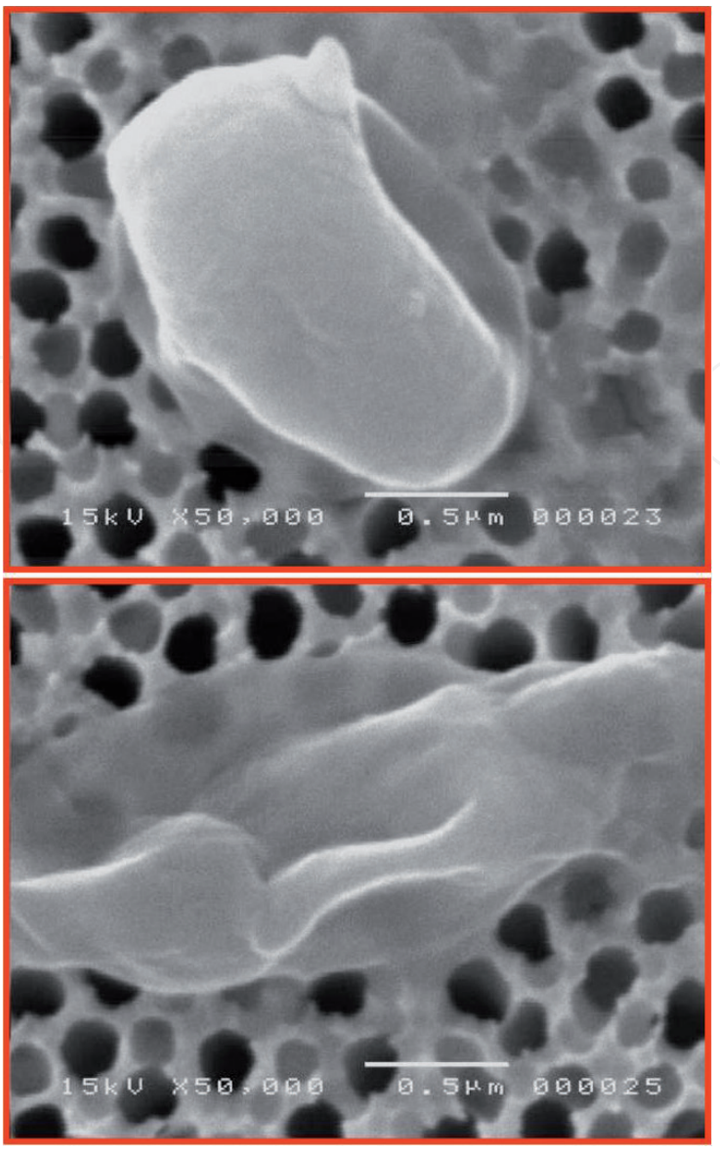


Figure 8.
The impact of DIC on spore destruction is coupled thermal and mechanical (explosion) effects.

Multi-Cycle DIC decontamination has demonstrated that decontamination ratio could not only be in function of temperature and time, but also in function of the number of DIC cycles. A study on skim milk powder showed an improvement decontamination concerning spores as well as vegetative forms [28].

5. Closing conclusion

By processing agricultural raw materials as functional food, industries must adopt processes able to satisfy various categories such as (1) preservation of functional properties, (2) good organoleptic quality of products, (3) safety and hygiene by perfectly bacterial decontamination and removing of fungi, (4) low energy consumption, (5) low time processing, and (6) friendly environmental processes. Convective airflow drying (CAD) is the most popular method to increase the shelf life of food products. However, traditional methods such as sun, solar, and airflow drying do not yield good-quality products, and else products run the risk to be contaminated with dust, dirt, insects, birds, microorganisms, fungi able to produce aflatoxins, etc. In this regard, various drying emerging technologies have been developed to improve the quality of dried products and

to reduce the time of processing. Nevertheless, it is essential to understand the main drawbacks of drying processes to really improve them. Then, a fundamental study of drying phenomena becomes essential. In this work, the mass and heat transfer phenomena during drying have been described, and the internal mass transfers were identified as the key limiting process of the whole operation. Concerning this matter, the instant controlled pressure drop technology (DIC) becomes a strategic technology for drying different types of natural functional foods. Thanks to its capacity to generate new porous structures on the food products, DIC allows surpassing the mass transfer limiting process. Hence, DIC technology could reduce the drying processing time, which leads a significant improvement in product quality. Moreover, thanks to its thermo-mechanical effect, it could also achieve perfectly bacterial decontamination of both vegetative forms and spores. DIC treatment allows to improve the availability of antioxidants, to reduce anti-nutritional, and allergic factors of foodstuffs. Finally, DIC treatment is low energy cost and friendly to the environment.

Nomenclature

A_{eff}	effective exchange surface between the product the external air (m^2)
a_w and a_{ws}	water activity for the whole material and at the surface, respectively
c_{ps}	specific heat capacity of the dried matter (J kg^{-1} K^{-1})
c_{pw}	specific heat capacity of the liquid water (J kg^{-1} K^{-1})
D_{eff}	effective Diffusivity (m^2 s^{-1})
ε_{abs}	absolute expansion (%)
φ	heat transfer (W m^{-2})
h	coefficient of convection heat transfer (W m^{-2} K^{-1})
k_p	coefficient of permeability mass transfer (m s^{-1})
K	Kelvin
λ_{eff}	thermic conductivity of the product (W m^{-1} K^{-1})
L_v	latent heat of evaporation (J kg^{-1})
M_w	molar mass of water (g mol^{-1})
P	vapor pressure surrounding the material
p_{wa}	vapor pressure of the air at a considered point (Pa)
p_{ws}	vapor pressure at the surface material (Pa)
p_{wT}	vapor pressure at the equilibrium temperature T (Pa)
dQ/dt	heat flow (W m^{-2})
dm_v/dt	vapor mass flows (kg m^{-2} s^{-1})
ρ	apparent density (kg m^{-3})
ρ_s	apparent density of dry material (kg m^{-3})
ρ_w	apparent density of water in the material (kg m^{-3})
ρ_v	density of vapor (kg m^{-3})
R	universal constant (8.314 J mol^{-1} K^{-1})
r	capillary radius (m)
t	time (s)
T	temperature
T_a	air temperature at a considered point
T_s	product temperature at the surface
v_w	absolute velocity of water flow within husks (m s^{-1})
v_s	Absolute velocity of solid porous medium (m s^{-1})
ν_v	kinematic viscosity (m^2 s^{-1})

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