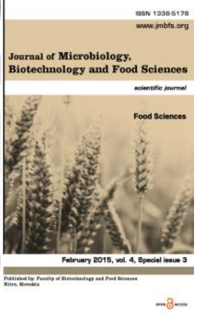

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FOOD PROCESSING TECHNOLOGY AS A MEDIATOR OF FUNCTIONALITY. STRUCTURE-PROPERTY-PROCESS RELATIONSHIPS

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ABSTRACT

During the last years, the food industry has been facing technical and economic changes both in society and in the food processing practices, paying high attention to food products that meet the consumers´ demands. In this direction, the study areas in food process and products have evolved mainly from safety to other topics such as quality, environment or health. The improvement of the food products is now directed towards ensuring nutritional and specific functional benefits. Regarding the processes evolution, they are directed to ensure the quality and safety of environmentally friendly food products produced optimizing the use of resources, minimally affecting or even enhancing their nutritional and beneficial characteristics. The product structure both in its raw form and after processing plays an important role maintaining, enhancing and delivering the bioactive compounds in the appropriate target within the organism. The aim of this review is to make an overview on some synergistic technologies that can constitute a technological process to develop functional foods, enhancing the technological and/or nutritional functionality of the food products in which they are applied. More concretely, the effect of homogenization, vacuum impregnation and drying operations on bioactive compounds have been reviewed, focusing on the structure changes produced and its relationship on the product functionality, as well as on the parameters and the strategies used to quantify and increase the achieved functionality.

Keywords: Homogenization, vacuum impregnation, drying, structure-property-process

Food technology and food processing: evolution towards functionality

Food processing can be defined as the operations set which allow manufacturing and/or preservation and/or distribution and/or marketing of food products from suitable raw materials. All food processing involves a combination of procedures to achieve the intended changes to the raw materials (**Fellows, 2009**).
Food processing is a very old industry and many of the processing operations have been practiced for millennia (**Norton, Fryer & Moore, 2006**). However, the "modern" food industry is about 200 years old. Thorne (**1986**) defines the beginnings of the industry to the production of the first-heat sterilization plan in France, developed by Appert in the early 1800s (**Norton, Fryer & Moore, 2006**). Since then, food process engineering has seen many developments especially over the last 35 years and thus the food industry itself has seen many changes (**Bruin & Jongen 2003**).
The food industry is now huge. It represents one of the most important branches in the European Union. It is 14.9 % of the total EU manufacturing sector, with a turnover of €1017 billion in 2010 (**FoodDrinkEurope, 2012a**). In the UK the food industry is the largest manufacturing sector, at 15 %, and it is responsible for 160 Mt CO_2 emissions and uses 367 TW/h annually, approximately 18 % of total UK energy use (**FoodDrinkEurope, 2012b**).
The first concern of food industry was, is and will be food safety. Although food is now safer than never before there are important safety targets still to be met (**Buckle, 2001**). For example, the presence of chemical contaminants in the food chain, such as PCB and dieldrin, is particularly troubling. In addition the emergence of new food pathogens, particularly viruses, as well as the re-emergence of known food pathogens, have captured considerable research attention (**Khoo & Knorr, 2014**).
During the last years, the food industry has been facing technical and economic changes both in society and in the manufacturing and food processing, that in turn had a significant impact on the entire food supply chain, up to the distribution of food to end consumers, forcing companies to pay high attention in food products that meet the consumers´ demands (**Bigliardi & Galati, 2013**). For this reason too, the study areas in food process and products have evolved mainly from safety to other topics as quality, environment or health. Due to changes in lifestyle, the increasing cost of healthcare, the steady increase in life expectancy and the desire of older people for an improved quality of life in their later years (**Kotilainen *et al*., 2006**) foods are no more intended to only satisfy hunger and to provide the necessary nutrients, but also and specially to prevent nutrition-related diseases and to improve physical and mental well-being (**Menrad, 2003; Robertfroid, 2000**). The improvement of the food products is now directed towards ensuring nutritional and specific functional benefit. Regarding the processes improvement, they are directed to ensure the quality and safety of environmentally friendly food products prepared optimizing the use of resources and affecting minimally or even enhancing their nutritional and beneficial characteristics. The challenge facing food technologists, engineers and companies is to investigate new techniques for food processing, monitoring food quality and providing the consumer with not only choice but their nutritional and physiological needs (**Buckle, 2001**).
The functional effect of a food or food component depends on the active component gaining access to the functional target site. The term bioaccessibility refers to the release of the nutritive compound from its food matrix into the digestive juices of the gastrointestinal tract (**Versantvoort *et al*., 2005**). Once this compound has been released, the proportion that is adsorbed and actually reaches the systemic circulation represent its bioavailability (**Turgeon & Rioux, 2011**). However, foods are mostly complex mixtures of macro- and micro- components that can trap active compound, modulate its release or inhibit its activity (**Chen, Remondetto & Subirade, 2006; Chen & Subirade, 2007**). Thus, the food matrix can have a significant influence on the activity or release on the key components. Selection and development of an appropriate both food vehicle and technological process that maintain the active molecular form until the time of consumption and deliver this form to the physiological target within the organism is an important step to the success of a functional food. The structure-property ensemble refers to the knowledge of structure and properties in a system, as well as the understanding of the relationships existing between the two concepts and, of course, the capability to predict the changes in food properties produced when any change in food structure occurs (**Aguilera, Chiralt & Fito, 2003**).
The aim of this review is to make an overview on some synergistic technologies that can constitute a technological process to develop functional foods, enhancing the technological and/or nutritional functionality of the food products in which they are applied. More concretely, the effect of homogenization, vacuum impregnation and drying operations on bioactive compounds have been reviewed focusing on the structure changes produced and its relationship on the product

functionality, as well as the parameters and the strategies used to quantify and increase the achieved functionality.

High pressures processing

High pressure homogenization process is a non-thermal technology applied in the food industry mainly used to disrupt pathogens and spoilage microorganisms, inactivate enzymes and improve the nutritional and technological quality of food products.
The high pressures homogenization was first applied in food industry for sanitization of food then started the applications directed towards inactivation of enzymes and finally the studies have been focused on the effect of high pressure homogenization on bioactive compounds. Although in the year 2000 the research paid attention to the microorganisms and enzymes inactivation, in 2014 focus primarily on functional applications (**Castagnini *et al*., 2014**).
The high pressure treatments used in food industry include hydrodynamic treatment (High Pressure Homogenization (HPH)) and hydrostatic treatments (High Pressure Processing (HPP)). Both of them can be applied to achieve the same goal but the action principle, the pressure level, the process conditions (temperature, residence time, inlet and outlet temperature, geometry) and the structural characteristics of food matrix determine the effect of each one. Hydrodynamics treatments (HPH) applies pressures from 3 to 500 MPa in continuous to fluid products, while hydrostatic treatments (HHP) are applied in batch systems to both solid and fluid products already packaged, using a pressure between 150 to 900 MPa. (**Castagnini *et al*., 2014**).
A lot of efforts have been made in order to elucidate the effect of HPH and HPP on bioactive compounds. In a general way, the published articles can be classified into three different groups:

1. The effect of pressure processing on bioactive compounds of juices when compared with fresh juices, thermal treated juices and treated juices by other techniques such as pulsed electric fields.
2. The effect of pressure processing on bioactive compounds of juices and their storage stability.
3. The effect of pressure processing on bioactive compounds and their *in vitro* and *in vivo* effect.

Table 1 shows some studies that evaluated the effect of homogenization treatments on functional and technological parameters of different products. The studies are classified according to the three groups explained before.
Fruits juices represent an important study area in the field because their high content in bioactive compounds and their sensitivity to thermal treatments. Thermal treatments applied to juices results in a cooked flavour that dislike consumers. In most cases, a compromise between treatment intensity, safety, and sensorial attributes is established without considering the effect on bioactive compounds. However, the application of high pressures is very promising because the resulting juices could be safe with high content in bioactive compounds, and with a fresh-like flavour. In all the observed cases the pressures treatments increased, maintained and when decreased, in a lower way than the thermal treatments, the determined bioactive compounds. Due to the positive results obtained for juices, the high pressure treatment was applied to other kind of products. For example, when applied to human milk (**Moltó Puigmartí *et al*., 2011**) the high pressure treatment is able to maintain the fatty acid, vitamin C, vitamin E, immunoglobulin A (IgA) (**Permanyer *et al*., 2010**) and lysozyme activity in a better way than Holder pasteurization.
The degradation of bioactive compounds during storage after high pressure treatment is equal or lower but never higher than those observed in thermal treated juices (**Velázquez-Estrada *et al*., 2013**). In most of cases, fresh-indicative parameters such as colour and aromatic compounds are maintained better in those juices treated by pressures than in thermal treated ones (**Vertvoort *et al*., 2011**).
A few studies have been carried out to determine the effect of homogenization on the *in vitro* or *in vivo* effect of bioactive compounds. HPH technology showed an ability to enhance survival of strains with probiotic effects or improve their functional properties (**Burns *et al*., 2008; Patrignani *et al*., 2009**). Low levels of HPH have been shown to increase acid and bile tolerance in some strains (**Muramalla & Aryana, 2011**) as well as the hydrophobicity and resistance to digestion. In the same way, HPH-treated cells induced a higher immunoglobulin A (IgA) response compared to untreated cells (**Tabanelli *et al*., 2012 and 2013**). It seems that HPH treatment is able to modify some features linked to the cell wall in probiotic lactobacilli and consequently altered the interaction with the small intestine. HPH has proved effect increasing the *in vitro* bioaccessibility of α- and β- carotene in carrot emulsions maintaining the ascorbic acid level, but decreasing the lycopene bioaccessibility in tomato emulsions (**Svelander *et al*., 2011**) due to an improving of the fiber network strength (**Colle *et al*., 2010**) demonstrating that not only the compound, but the food matrix has a high influence on *in vitro* bioaccessibility.
Current knowledge indicates that the use of pressure treatments has been established as a novel non-thermal technology, able to maintain and improve the nutritional and quality properties of food products when compared with those resulting from thermal treatments. The hypothesis established is that under the pressure influence, small molecules, such as volatile compounds, pigments, amino acids and vitamins remain unaffected, due to their relatively simple structures. In contrast, larger molecules, such as proteins, enzymes, polysaccharides and nucleic acids, may be altered (**Balci & Wilbey, 1999**).

Vacuum impregnation

Vacuum impregnation technology (VI) is a mass transfer operation between liquid medium and a solid porous food. Pressure gradients created in the system with the capillary pressure in the entrance of pores promote a significant gas and liquid transfer between the liquid and solid. Based on porous structure of some foods and the existence of gas occluded on it, **Fito (1994)** and **Fito & Pastor (1994)** explained the hydrodynamic mechanism, as the main phenomenon involved in the vacuum impregnation operation. When the solid product, submerged into a liquid, is submitted to subatmospheric pressures, the gas occluded into the solid undergoes an expansion to equilibrate with the reached pressures. This means, a degasification of the porous structure depending on the applied pressure, and on the other hand a penetration of liquid by capillarity when the equilibrium is reached. Furthermore, the restoration of the atmospheric pressures in the system will promote a new pressure gradient that will act as a driving force; the intercellular spaces of the solid product will be filled partially from external liquid. The liquid amount which impregnates the solid structure will depend on degasification level and therefore on the applied pressure. The liquid penetration produced by pressure gradients is reversible and controlled by gas compression or expansion in the intercellular spaces. Different studies shown that HDM phenomena occurs coupled with deformation-relaxation (DRP) one in the solid matrix, with viscoelastic properties, of porous food. The HDM and DRP phenomena are greatly affected by food microstructure and mechanical properties, causing important changes in the physical properties of the product. Thus, vacuum impregnation has been considered as a useful way to introduce desirable solutes into the structural matrix of porous foods, conveniently modifying their original composition without affecting their integrity.
If considering the effect of the operation on bioactive compounds, the articles published can be classified into two different groups:

1. The effect of VI on bioactive compounds added to the product in order to achieve a qualitative, technological functionality;
2. The effect of VI on bioactive compounds added to the product in order to achieve a nutritional functionality;

Table 2 shows some studies that evaluated the effect of VI on bioactive compounds from different products.
Quality improvement of porous structure of foods by VI pre-treatment is largely due to the use of a gentle product treatment at a relatively low processing temperature, thus minimizing heat damage to plant tissues, and preserving colour, natural flavour, aroma and any heat sensitive nutrient components. This technology has been widely used as a pre-treatment before drying, freezing and frying (**Bolin & Huxsoll, 1993**). VI is effective in preventing discoloration of fruit pieces from enzymatic and oxidative browning without using antioxidants due to removal of oxygen from the pores (**Alzamora *et al*., 2000; Barbosa-Cánovas & Vega-Mercado, 1996**). There is a large amount of literature focused on the effects of the vacuum level on the structure and mechanical properties of the food products during VI operation, as well as the effects of the impregnation liquid on the resulting product structure and mechanical properties (**Carciofi, Prat & Laurindo, 2012**; **Guilleim *et al*., 2008; Fito & Chiralt, 2003; Fito & Pastor, 1994**). Some studies focused on the metabolic consequences of VI that are provoked by structural modifications induced by the pressure changes, the impregnated molecules and/or anaerobic stress (**Panarese *et al*., 2014**). The positive results obtained by this technology made it interesting to develop minimally processed products with high structural and sensorial attributes and also with an increased shelf life (**Moreno *et al*., 2012; Occhino *et al*., 2011**).
The possibility to include in the structural matrix of a porous food bioactive compounds evidences VI as an effective technology for new products design. A lot of studies are found in literature in which fruits and vegetables are impregnated with different isotonic or hypertonic solutions of one or more bioactive compounds, in order to achieve a considerable amount of the recommended daily intake in the final product. In this regard, it is noteworthy the increasing tendency to change the impregnation liquid formulated with purified extracts of bioactive compounds by fruits juices with high content in bioactive compounds in its raw composition (**Betoret *et al*., 2012**; **Castagnini, 2014**).
Although in recent years a large number of studies have shown the beneficial effect of some components on health, there is a growing number of authors who argue that the consumption of whole foods can provide higher benefits than consumption of physiologically active compound in tablet or capsule form. The effect of physiologically active compounds individually differs from the effect of their mixture. It has been shown that the various nutrients provided by food products can have a significant synergistic effect. Hesperidin (the main flavonoid of mandarin juice) is more effective when administered in combination with vitamin C (**Garg *et al*., 2001**). The combination of all physiologically active compounds presents in fruits and vegetables are responsible for their high antioxidant activity. Vitamin C of apple with skin supposes to be the 0.4 % of all

its antioxidant activity (**Liu *et al.*, 2003**). Moreover, the compounds presents in food rarely produce toxicity although consumed in big portions; however in tablets or capsules containing physiologically active compounds, there are excipients that consumed in large quantities may be harmful (**Codoñer-Franch *et al*., 2010**). The inclusion of physiologically active compounds into a structural matrix by VI can be a protection against degradation reactions but in the same time, the new structure developed must allow their release in the appropriate way and time so the organism will be able to use them. To the best of our knowledge the studies focused on the protection that VI technology can provide to the bioactive compounds are scarce. **Watanabe *et al*., (2011)** studied the effect of VI using sucrose solution on stability of anthocyanin in strawberry jam. Results obtained suggested that the impregnation of sucrose in advance of the jam preparation stabilized the anthocyanin compounds more strongly that the mere addition of sucrose during the preparation. **In 2013a,b Codoñer *et al*.,** studied the *in vivo* effect both in humans and in animals of an apple snack enriched with mandarin juice by vacuum impregnations with positive results in all cases.

Drying technologies

Drying is an energy intensive unit operation in food processing to reduce product moisture content to a level that is safe for storage and transportation, to avoid microbial multiplication and inactivate microbial activity.

Drying is a well-studied unit operation in process engineering where a major objective is to dewater a material at increasingly faster rates optimizing energy expenditure.

Food technologies are usually faced with drying biological structures that must perform in the dry state and as rehydrated products as well. Drying technology is applied in the food industry not only for preservation but also to manufacture foods with certain characteristics. To achieve this objective is necessary to know how structures are transformed during processing (**Aguilera, Chiralt & Fito, 2003**).

The nature of the process along with the food structural characteristics results in a very marked effect on the quality characteristics of the final product. Overall, the quality characteristics of the final product are significantly affected by the process conditions and the way it is conducted. Thus, drying operations need to be precisely controlled and optimized in order to produce a good quality product that has the highest level of nutrient retention and flavour whilst maintaining microbial safety.

A lot of articles have been published modelling the different drying operations and studying the effect of the process on the quality characteristics of the final products. The effect of the operations on single, specific bioactive compounds has been studied too. However, the effect of the operation on the functional effect on whole foods is still scarce.

The unique features of this technology make it one of the most used. The materials preserved by dehydration vary a lot, since fruits and vegetables to probiotic microorganisms and animal products in the food area, but also other biological materials with important physiological activities such as human blood cells and mononuclear cells from umbilical cord blood.

In most of cases the dehydration step involves the application of extreme temperature conditions (very low temperatures in the case of freeze-drying, and very high in the case of other methods such as air drying, spray drying ...) that cause irreversible damage due primarily to:

- Changes in cellular structures (cell wall, cell membrane ...) that constitute biological tissues and induce changes in key properties responsible for their functionality (cell membrane permeability, mechanical strength of the wall-membrane assembly ...).
- Changes in the chemical structures responsible for the biological value of nutritious components (protein, fat ...). The structural changes also cause changes in the technological functionality that these compounds give the food to which they belong.
- Reactions, mainly oxidation reactions, than decrease the functional value of nutritive compounds (vitamin, antioxidants…).

The research in this area is aimed at finding solutions not only to reduce the negative effects of dehydration on biomolecules, but in some cases even increasing the functional value of some components. Thus the main actions included on the papers published in recent years are summarized in table 3 and are:

1. Addition of compounds with protector effect, such as various sugars (e.g. glucose, fructose, lactose, mannose), sugar alcohols (e.g. sorbitol and inositol) and non-reducing sugars (e.g. sucrose, trehalose). A variety of protectants have been added to the drying media before freeze-drying or spray-drying to protect the viability of probiotics during dehydration, including skim milk powder, whey protein, trehalose, glycerol, betaine, adonitol, sucrose, glucose, lactose and polymers such as dextran and polyethylene glycol. The beneficial effects of the protectants, seems to be related to their protective effect on proteins and cell membranes (**Leslie *et al*., 1995**).
2. Creation of structural elements with protective effect.
3. Induction of positive structural changes.

CONCLUSION

Many studies show the relationship between the structural characteristics of food and their bioactive compounds together with the technological and nutritional achieved functionality. While processing operations generally have a negative effect on this functionality, studies show that proper management of the processing technologies can result in a less negative effect and in some cases the overall functionality can be improved. Applying high pressure homogenization leads, in many cases, structural changes that improve the bioaccessibility and/or the bioavailability of bioactive compounds such as probiotic microorganisms or β-carotene. The vacuum impregnation operation allows the incorporation of technological and/or bioactive compounds into natural structures taking advantage of both the protective effect of these ones and the synergistic effect of certain compounds. The negative effects related to the application of extreme temperatures in drying operations can be minimized by incorporating ingredients that protect structural elements or creating protective structures.

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