

Some aspects of vegetable pickling processes

Algunos aspectos de la elaboración de encurtidos vegetales

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A topical review of pickled vegetables is presented that encompasses scientific considerations relevant to processing with the ultimate goal of generating interest for this ancient preservation technique. The emphasis is placed on the potential application of pickling to a group of high quality vegetables, and directing research and development pertaining to pickling in a more educated way. A critical literature survey is presented on issues such as transport of solutes, *in situ* fermentation, and textural changes throughout the pickling process.

Keywords: lactic fermentation, pickles, texture

Se han analizado los aspectos más relevantes relacionados con la elaboración de encurtidos vegetales con la finalidad de atraer el interés por este antiguo sistema de conservación, haciendo énfasis en su aplicación potencial para la producción de verduras de alta calidad y en las directrices de la I + D vinculada a los encurtidos. Se hace un análisis crítico de la bibliografía relacionada con el transporte de solutos, la fermentación *in situ* y la evolución de la textura durante la fermentación de los encurtidos.

Palabras clave: fermentación láctica, encurtidos, textura

INTRODUCTION

From a historical point of view it appears that preservation of vegetables by pickling was initially a requirement to ensure adequate supplies of food in Northern climates as the warm season elapsed. The advent of alternative preservation techniques, however, soon led to the use of pickling as a way of adding unique flavours to such vegetables.

Pickles can be obtained by plain immersion of raw, blanched or pre-cooked pieces (or entire portions) of vegetables in aqueous solutions of food grade organic acids (e.g. acetic, citric, or lactic acid). The final formulation of the brine often includes salt and brown sugar (or caramel). Another pickling option is the

generation *in situ* of the aforementioned organic acid(s) by fermentation of the sugars eventually leached from vegetables submerged in the brine; this is brought about either by adventitious microflora or deliberately added starters. The latter approach offers the potential for development of specific tastes in the final product.

Fermented vegetables (including vegetable pickles) have a great importance in Europe as does fermented meat (Kato *et al.*, 1994; Katsaras and Dresel, 1994), fermented fish (Rodríguez Jerez *et al.*, 1994), and foodstock silage (Charmley *et al.*, 1994); Moisis and Heikonen, 1994). German and Scandinavian countries have a tradition in the production of such fermented vegetables as sauerkraut, whereas in Mediterranean countries fermented olives are highly appreciated and extensively exported to Africa and the Middle East. In addition to lactic acid pickled olives (which accounts for a sustained overall yearly

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production of around 1×10^6 t), there is currently an increasing interest in lactic acid pickled vegetables by the pickling companies that act as subsidiaries of fast-food enterprises, especially on account of the development of vegetable based snacks which demand sugar depletion prior to the deep frying process; in the USA, for example, large amounts of pickled cucumbers are produced every year, and this product on its own accounts for around 40% of the overall production of fermented vegetables in that country (Humphries and Fleming, 1989). Despite their excellent weather conditions for production of a variety of vegetables, several countries still have a large net import of fermented vegetables; for example, in 1994 Portugal imported around 593,000 ECU of fermented vegetables mainly from Germany and Spain (about 92%) and to a lesser extent, from Greece, but only exported around 385,000 ECU (Anonymous, 1995). There is obviously a considerable internal market for fermented vegetables, but the availability of, and the interest by, national manufacturers has apparently not yet reached the critical point at which the technology will be put to use effectively.

PROCESSING

Pickles may be classified according to the nature of the process of generation of organic acid, i.e. fermented or unfermented. They can also be classified based on the taste of the final product obtained (Binsted *et al.*, 1962): (i) sour pickles; (ii) sweet pickles; (iii) sweet/sour pickles; (iv) dills; and (v) chutneys. Most pickled vegetables fall into one of these categories, encompassing (but not limited to) white cabbage, cauliflower, gherkins, onions, beetroots, and *Capsicum minimum* chillies (Tabasco™). The degree of sweetness or sourness is imparted by the balance between the types and amounts of organic acids and sugars present. Dill pickles are obtained by adding spices to sour solutions, and the most commonly used varieties are pepper (*Piper nigrum*) as the whole fruit (black pepper) or the pericarp-free fruit (white pepper), jamaic pepper (*Piper officinalis*), cayenne pepper (*Capsicum frutescens*), cumin seed (*Cuminum cyminum*), ginger (*Zingiber officinale*), coriander (*Coriandrum sativum*), paprika (*Capsicum annum*), mustard seed (*Sinapsis alba*), capers (*Capparis spinosa*), and dill (*Anethium graveoleus*) (after which the process is named). If spices are added to high final concentrations then pickles are termed chutneys.

In order to assure extended shelf-lives and preservation of colour, unfermented pickles require a preliminary step of heat processing (e.g. blanching),

which promotes denaturation and concomitant deactivation of native enzymes that would otherwise be implicated in texture softening (e.g. polygalacturonase) and off-flavour development (e.g. peroxidase). Conversely, fermented pickles do not usually undergo heat processing (Fleming *et al.*, 1993a), and hence fermentation pickling may be viewed as a minimal preservation process. The final forms of such pickles are microbiologically stable provided that: (i) virtually all carbohydrates which would ever be available in solution due to leaching have been duly reduced into organic acids; (ii) the final pH is low enough to prevent spore-forming bacteria from growing; (iii) the oxygen potential is low enough to avoid growth of yeasts, molds, and aerobic bacteria; and (iv) the water activity within the vegetable material is low enough to slow the development of secondary microflora to negligible levels.

Most pickling processes reported to date can be represented by the generic processing diagram shown in Figure 1. Comprehensive scientific and technological studies have encompassed pickling of vegetables such as cabbage (*sauerkraut*) (Pederson and Albury, 1953, 1954; Pederson, 1971), carrots (Niketic-Aleksic *et al.*, 1973; Aukrust *et al.*, 1995), cucumbers (Etchells *et al.*, 1975a, 1975b), olives (Díez *et al.*, 1985; García *et al.*, 1992), and tomatoes (Beltrán-Edeza and Hernández-Sánchez, 1989).

In pickle processing there are three major issues to be addressed: transport of solutes, generation of acid, and textural effects. These topics are discussed in detail next.

Transport of solutes

Since pickles consist, by definition, of vegetable material submerged in a brine, transfer of solutes between the liquid and the solid phase will occur irrespective of whether such solutes are deliberately added (e.g. salt or spices) or generated therein (e.g. lactic acid by fermentation). Besides the practical interest of nutrient transfer which directly correlates with final organoleptic quality and drained weight of pickles, unrecovered nutrients in residual processing water may account for high biological oxygen demands (above 500 ppm) (Braile and Cavalcanti, 1979) and high salt concentration (above 10% w/v) (Díez *et al.*, 1985), both of which raise serious environmental problems. Owing to the fact that transport of solutes under the processing conditions commonly employed is essentially an unselective process, it is expected that transport of vitamins, flavour compounds and colour compounds out of the vegetables and transport of acids and salts into

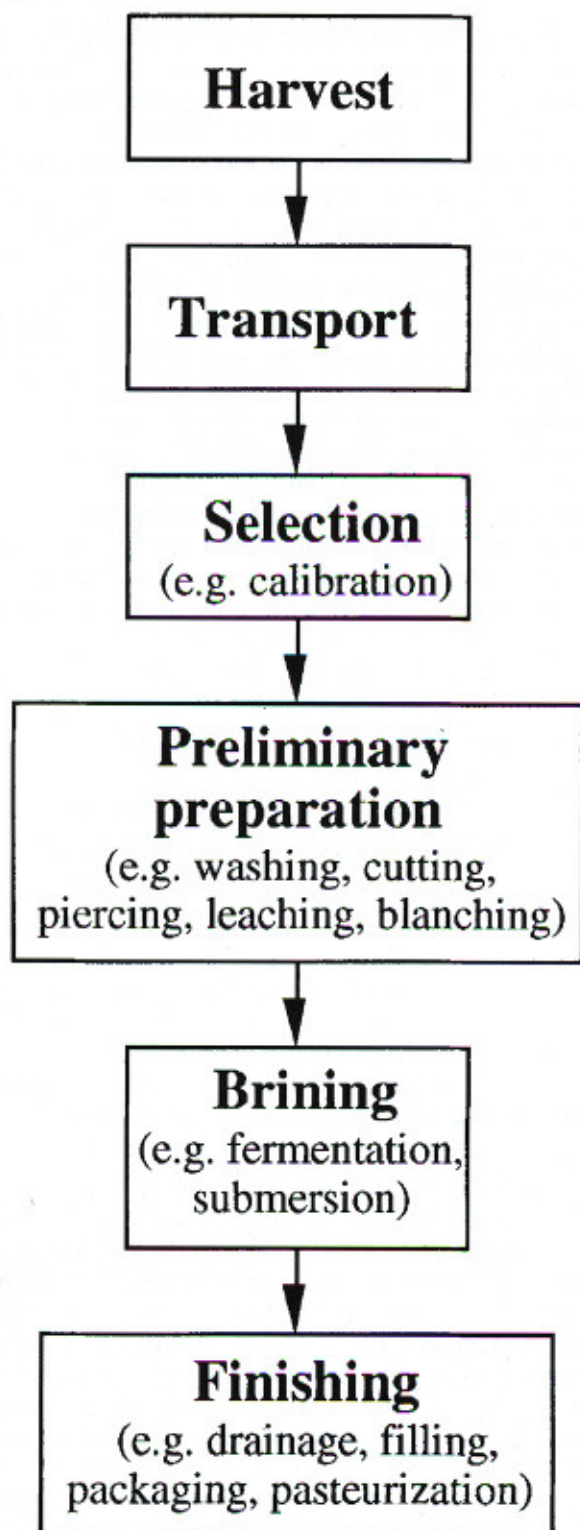


Figure 1. Flowchart showing a generalization of the pickling process.

Figura 1. Esquema general de la elaboración de encurtidos.

the vegetables will take place, both causing deleterious effects upon texture.

Several approaches have been taken in order to rationalize such mass fluxes, including osmotic pressure imbalances between the vegetable material and the brine (Biswall, 1989; Toupin *et al.*, 1989), dual sorption of solutes (Soddu and Gioia, 1979), and molecular transport by diffusion (Schwartzberg and Chao, 1982; Potts *et al.*, 1986; Oliveira, 1988; Oliveira and Silva, 1992; Moreira, 1994).

Interchange of solutes between the vegetables and the aqueous solutions in which they are submerged occurs by convection, molecular diffusion or eddy diffusion. While convection and eddy diffusion play important roles in mass transfer in the liquid phase, diffusion due to random molecular motion dominates in the solid matrix (Schwartzberg and Chao, 1982). The extent of solute transfer is controlled by the Biot number, which in turn depends on: the mass transfer coefficient of the liquid brine; the partition coefficient between the liquid brine and the solid matrix; and the apparent diffusivity within the solid. Because foods are structurally heterogeneous, the apparent diffusivity coefficient in the solid matrix is a function not only of the intrinsic diffusivity of the liquid filling up the pores, but also on the size and shape of such pores, on the ionic strength prevailing therein (as a consequence of salt and acid concentrations and pH) and on the nature of the solid phase. This last point is of particular relevance for vegetable tissues because, in view of osmotic phenomena, they are dynamic structures encompassing intact cells, disrupted cells, intercellular fluids and loose cell walls. Such complex networks of polysaccharides and proteins (Carpita, 1985) are able to gain or lose water and thus affect the resistance offered by the solid matrix to Brownian motion of solutes (Toupin *et al.*, 1989). This issue is further complicated by the temperature prevailing throughout processing because the vegetable tissue is still alive, and so active transport of solutes will also occur at room temperatures (Salisbury and Ross, 1978).

Transport of solutes is crucial if fermentation is to take place for the generation of the organic acid required by pickling, especially in what pertains to the pH and levels of fermentable carbohydrates in the brine.

Generation of acid

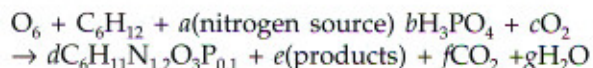
If the organic acid required for pickling is generated *in situ* by fermentation, two major facts should be borne in mind (Fleming, 1982): (i) nutrients are provided by leaching from the vegetable material, which,

due to the large size of such molecules, is usually possible only after disruption of the cell membrane; and (ii) fresh vegetables contain various wild microorganisms (epiphytic microflora), most of which are not lactic acid bacteria and many of which are potentially involved in spoilage phenomena. Any industrial fermentation process must consider aspects of cell physiology (including growth requirements), reactor engineering (including fermentor operation, instrumentation and control), and chemical kinetics (including reaction stoichiometry and rates of substrate depletion and product formation) (Crueger and Crueger, 1984; Bailey and Ollis, 1986).

The scope of microbial physiology is catabolism, that is a network of routes for converting chemical energy of selected carbon sources to a usable form at the intracellular level. The selected carbon sources are hexoses (usually consubstantiated in glucose) or pentoses, whereas the usable intracellular form is ATP. There are two major alternative possibilities for carbon source use: aerobic (that implies complete oxidation of glucose and where molecular oxygen is the final electron acceptor), which leads to generation of significant amounts of ATP; and anaerobic (that results from incomplete oxidation of glucose and where reduced organic compounds are the final electron acceptors), which leads to generation of approximately 20 times less ATP.

The organic compounds generated from anaerobic respiration (or fermentation) are usually considered to be primary metabolites if the rates of their synthesis correlate linearly with the rates of cell growth, otherwise they are termed secondary metabolites. The metabolic route currently accepted for the production of lactic acid from glucose (the most common carbon source) consists of the Embden-Meyerhof-Parnas pathway for glycolysis that yields pyruvate followed by reduction of this intermediate compound to lactic acid (Figure 2).

The general chemical equation for growth and primary product synthesis (energy-consuming phenomena usually referred to as anabolism) can in general be given by:



where a to g are stoichiometric coefficients, and where the chemical formulae of the nitrogen source and of the products depend on the type of medium utilized. The aforementioned chemical balance equation has proved useful in the design of fermentation media and as a guideline for general assessment of fermentation processes. It should be emphasized that cell

growth will stop when the medium is depleted of an essential nutrient or if the cells produce an inhibitory/toxic product; toxic compounds may also be a constituent of the fermentation medium.

In attempts to characterize the kinetics of fermentation processes, several parameters are in general use and of general acceptance; specific growth rate, growth yield, metabolic quotient, and product yield. The growth rate can be defined as the mass ratio of new cells formed (usually on a dry weight basis) to the mass of existing cells per unit time; the growth yield is the mass ratio of new cells formed to the mass of substrate consumed (the growth yield is thus higher for aerobic than for anaerobic growth, since the net energy balance favours complete substrate oxidation); the metabolic quotients translate quantitatively the mass variation of a given metabolic component (e.g. a product of a by-product) per unit biomass and per unit time; and the product yield is the mass ratio of product formed to the mass of nutrient substrate consumed. The growth rate and the (limiting) substrate concentration in dilute media can be empirically correlated with one another via the Monod equation. In addition to growth, which uses energy to synthesize new biomass and actively transport compounds through the cell membrane across unfavourable concentration gradients, energy is also required for repair and mobility; this latter energy, usually of relevance for resting cells, is lumped under the general designation of maintenance energy.

In media of complex composition, such as those involved in vegetable fermentation, four stages are considered in descriptions of the overall fermentation process: (i) initiation (usually involving various Gram-positive and Gram-negative bacteria); (ii) primary fermentation (involving lactic-acid bacteria and yeasts); (iii) secondary fermentation (involving mainly yeasts); and (iv) post-fermentation (carried out by oxidative yeasts, moulds, and bacteria). A natural pickling fermentation usually starts with *Enterobacter cloacae* and *Erwinia herbicola* (Andersson, 1984; Andersson *et al.*, 1990), but a multitude of other microorganisms soon start growing over a wide range of temperatures and salt concentrations (Fleming, 1982) and a wide range of salt and acetic acid concentrations (Durán *et al.*, 1994). A good example of such microorganisms is *Leuconostoc mesenteroides*, which uses hexoses (e.g. glucose and fructose) as the preferred carbon sources (but which may also use pentoses such as arabinose, xylose and dextran) yielding equimolar amounts of lactic and acetic acids, as well as ethanol and mannitol (Andersson, 1984; Andersson *et al.*, 1990). These compounds are important because they further react with one another to

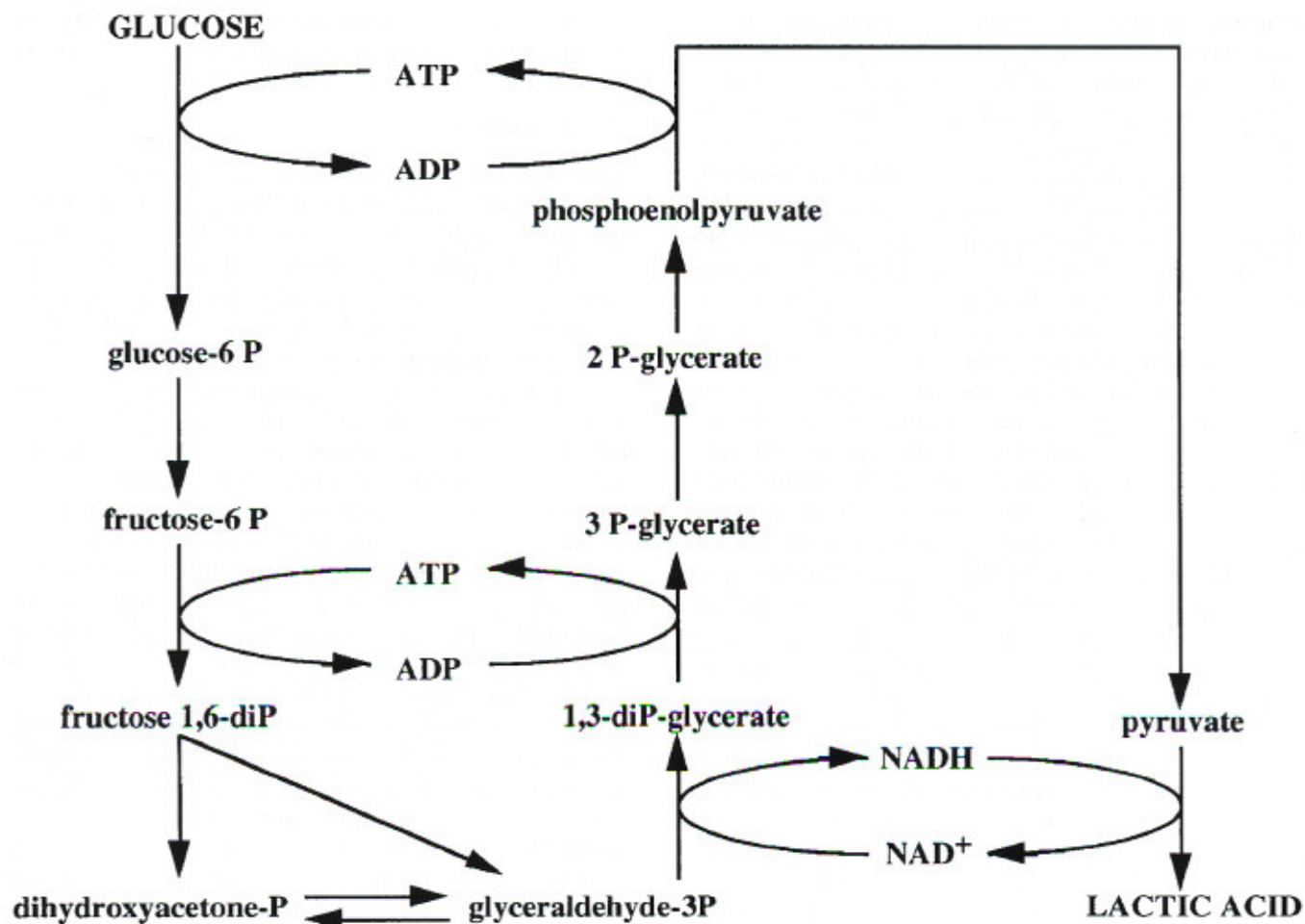


Figure 2. Pathway of lactic fermentation (adapted from Bailey and Ollis, 1986).

Figura 2. Ruta de la fermentación láctica, tomada de Bailey y Ollis (1986).

give low molecular weight esters, which have been implicated in unique fruity food flavours, and because the intrinsic bitterness of the vegetables brought about by dextran may be partially eliminated. The growth of these microorganisms is usually followed by proliferation of *Lactobacillus plantarum*, a facultative heterofermentative bacterium that plays an important role due to its high lactic acid production (up to around 1.5% v/v). At this stage it would be advisable to discontinue the fermentation process and not carry out the secondary and post-fermentation processes. Nonetheless, the buffering capacity of the brine and the inventory of fermentable sugars therein often lead to growth of acid-tolerant microorganisms, e.g. *Lactobacillus brevis*, which are compulsory heterofermentative bacteria (Andersson, 1984); in addition to the production of organic acids that will eventually

yield the sharp acid characteristics of the final pickles, they may also cause a processing problem known as 'bloater' (the tendency of the pickles to float due to gas generation) coupled with the promotion of favourable conditions for growth of oxidative and fermentative yeasts (secondary fermentation, usually by mixed cultures of *Torulopsis*, *Saccharomyces* and *Candida* spp.) and ending with post-fermentation problems caused by growth of the moulds *Penicillium*, *Fusarium* and *Cladosporium* spp. (Andersson, 1984).

Since production of organic acid(s) is the main goal of fermentative processing of vegetables for pickling, special care should be exercised in assessing the consequences thereof: pH (a measure of available hydrogen ions); titratable acidity (a measure of actual hydrogen ion concentration); volatile acidity (a measure of total concentration of volatile acids); and

buffering capacity (a measure of the balance between acid and base conjugate pairs). In spite of their low toxicity to humans, acetic and lactic acids display antimicrobial action (Smulders *et al.*, 1986; Adams and Hall, 1988); such action results from the ability of the lipophilic, undissociated acid molecules to penetrate the bacterial cell membrane, and once in the cytoplasm, to release hydrogen ions and conjugate bases that interfere with ATP transfer. Hence, the antimicrobial effect of these organic acids depends on the pH of the brine as compared to their pK_a (3.86 for lactic acid and 4.75 for acetic acid), and is enhanced when the pH is below the dissociation constant; because this decrease is accompanied by an increase in the buffering capacity of the brine, the antimicrobial effect mentioned above will become more apparent as fermentation progresses (Stamer, 1983). The titratable acidity (also referred to as free acidity) is, together with pH, an important characteristic of the fermentation process; not only is the growth of undesirable microorganisms restricted, but lysis of the microorganisms may also take place with the resultant release of amino acids, which are known, in free form, to contribute to food flavours. On the other hand, the D- and L- isomers of lactic acid do not have the same physiological activity; whereas L(+)-lactic acid is utilized in gluconogenesis similar to that prevailing in human metabolism, D(-)-lactic acid, requires a non-specific α -hydroxyoxidase which is not normally produced in human beings (Steinkraus, 1983). Although most strains produce racemic mixtures of L(+)- and D(-)- lactic acid, some *Lactobacillus* spp., prevailing in pickling fermentation, produce L(+)-lactic preferentially, and this beneficial effect can be coupled with their notable probiotic activity (Friend and Shahani, 1984; Daeschel and Klaenhammer, 1985; Daeschel *et al.*, 1990; Degnan *et al.*, 1994; Ruiz-Barba *et al.*, 1994) Unlike the contribution of acetic acid and propionic acid to colour retention (by chelation phenomena), lactic acid, malic acid, and tartaric acid accelerate loss of carotenoid pigments in some vegetables (Juliot *et al.*, 1989) a phenomenon that poses processing problems pertaining to organoleptic appearance.

If direct acidification of vegetables by the deliberate addition of one (or more) organic acid(s) is selected rather than generation of these acid(s) by *in situ* fermentation, then shorter processing times permit maintenance of fresh flavours. However, such advantage is usually offset by specific downstream processing (Monroe *et al.*, 1969; Lonergan and Lindsay, 1979; Chen and Peng, 1980; Basel and Gould, 1983) which depends on the vegetable in question; for carrots, aeration during acidification causes the colour

to fade rapidly due to oxidation of β -carotene, which also yields floral-like aromas (Juliot *et al.*, 1989).

Textural effects

Vegetable tissues are assemblies of cells with various characteristics, depending on their specific functions, but with a similar origin. The living part of the plant is called symplast (Salisbury and Ross, 1978), and includes the cytoplasm of all cells (including large cytoplasmic vacuoles). A schematic representation of a 'typical' vegetable cell is shown in Figure 3.

The cytoplasm of adjoining cells is connected through pores in the cell walls (called plasmodesmata), and these pores allow the symplastic transport of water and small solutes (Toupin *et al.*, 1989); conversely, apoplastic transport consists of exchanges between the cells' interior (intracellular space) and exterior (intercellular tissue) across the cell membrane. One of the main problems of the apoplastic exchange of solutions is that the uptake of water and the uptake of solutes are never coupled to one another within a living plant tissue; in fact, the latter is an active energy-requiring process, while the former is a passive process controlled by osmotic pressure differentials that, across the cell membrane, can easily range from 1000 to 3000 bar (Salisbury and Ross, 1978). In view of such high pressures, it is widely accepted that sieve cells can function as the safety valves of the plant because large gas bubbles are filtered out, thereby avoiding cavitation problems in the cell tissues. Under natural conditions, parts of living plants are able to survive anoxic periods, which, due to the absence of oxygen as final electron acceptor, implies sugar starvation, lactic acid production, and proton release from vacuoles; in order to overcome such periods plant cells are equipped with radical detoxifying systems consisting mainly of peroxidases and antioxidants (Pfistersieber and Brandle, 1994).

Vegetables are composed of two major types of tissues: non-differentiated tissues (meristem) and differentiated tissues (which are specialized in functions such as coating, physical support, translocation, secretion, excretion, and storage, and in which the cells can remain alive or become progressively inert). These two types of tissues can be reversibly transformed into one another, although reversal of a differentiated tissue to a meristematic tissue (e.g. dicotyledon species) is seldom observed. The tissue constituting the root of a superior plant is depicted in Figure 4. The main vegetable coating tissues are the epidermis and the suber; the first, found in the leaves, flowers, fruits, and young roots, consists of

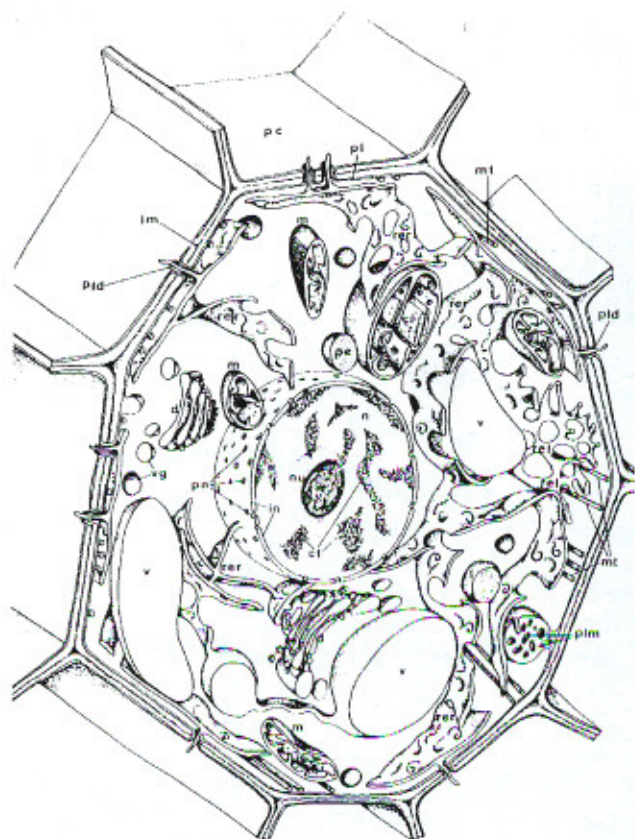


Figure 3. Schematic three dimensional representation of a vegetable cell (adapted from Salema *et al.*, 1980). pc, cell wall; lm, intermediate membrane; pld, plasmodesmata; pl, plasmolemma; mt, cortical tubes; plm, plasmolemasome; rel, smooth endoplasmic reticulum; rer, non-smooth endoplasmic reticulum; d, dictiosome; vg, Golgi apparatus; v, vacuoles; l, lysosome; pe, peroxisome; m, mitochondrium; cl, chloroplast; n, nucleus; pn, nuclei pores; nu, nucleolus.

Figura 3. Representación esquemática tridimensional de una célula vegetal, tomada de Salema *et al.* (1980). pc, pared celular; lm, membrana intermedia; pld, plasmodemo; pl, plasmolemo; mt, tubos corticales; plm, plasmolemasona; rel, retículo endoplásmico fino; rer, retículo endoplásmico grueso; d, dictiosoma, vg, aparato de Golgi; v, vacuolas; l, lisosoma; pe, peroxisoma; m, mitocondria; cl, cloroplasto; n, núcleo; pn, poros del núcleo; nu, nucleolos.

chlorophyll-free cells protected by wax, and can be made of simple shallow cells or structured cells (as in tomatoes). The main vegetable translocation tissues are specialized in upward movement of water and mineral ions (xylem) or in downward movement of organic assimilates (phloem) (Richardson, 1975). The

xylem appears to function primarily as a support rather than a transport tissue, and consists of functional conduits composed of dead cells whose central lumen contains no cytoplasm. The phloem tissues of most plants are composed of a number of live, morphologically different cells (sieve elements, companion cells or parenchyma) which contain living cytoplasm but no nucleus and whose large lumen is filled with phloem protein (slime). The youngest sieve elements have their side and end cell walls transversed by the plasmodesmata. Transport in the phloem can be bidirectional and is due, in a living plant, to pressure drops, electro-osmosis, and transcellular protein strands (Salisbury and Ross, 1978). If both these tissues in the root of a superior plant are considered, it is apparent that as the root grows in diameter, the cells between the xylem and phloem form a vascular cambium that produces mostly xylem tissue to the inside and phloem tissue to the outside. Both xylem and phloem are surrounded by a layer of living cells, the pericycle; an extra layer of cells (endodermis) is located just outside the pericycle; and the outside of the endodermis is enrobed by several layers of living cells (often with considerable intercellular space) called the cortex. In view of the complex morphological characteristics of plant tissues, attempts to study the fundamentals of mass transfer in plant tissues should involve the description of such structures (Soddu and Gioia, 1979; Oliveira, 1988; Toupin *et al.*, 1989; Moreira, 1994).

As a crispy texture is a desired characteristic of pickles (Bell *et al.*, 1972), softening of vegetables resulting from pickling is one of the major concerns of pickling industries. The walls of the vegetable cells are rich in pectic polysaccharides, celluloses, and hemicelluloses; for example, carrot tissues have alcohol-insoluble residues that can be hydrolysed by the maceration process (a consequence of pectinase action) or the liquefaction process (a consequence of pectinase and cellulase action). Although processes such as depolymerization of the β -elimination type, demethoxylation, and complex formation have been implicated in textural decay (Buren, 1979), it is widely accepted that the softening phenomenon is chiefly a natural consequence of the breakdown of pectic compounds (Fleming, 1982), and may have physical, chemical, and/or biochemical causes (Bell *et al.*, 1972; Diez *et al.*, 1985). The production of natural extracellular enzymes by tissues of superior vegetables has been reported as an example of such biochemical causes; β -glucanase (Kurosaki *et al.*, 1991), exo- and β -galactosidase (Konno and Katoh, 1992), β -polygalacturonidase (Konno *et al.*, 1989), and three isoenzymatic forms of pectinesterase (Markovic, 1978).

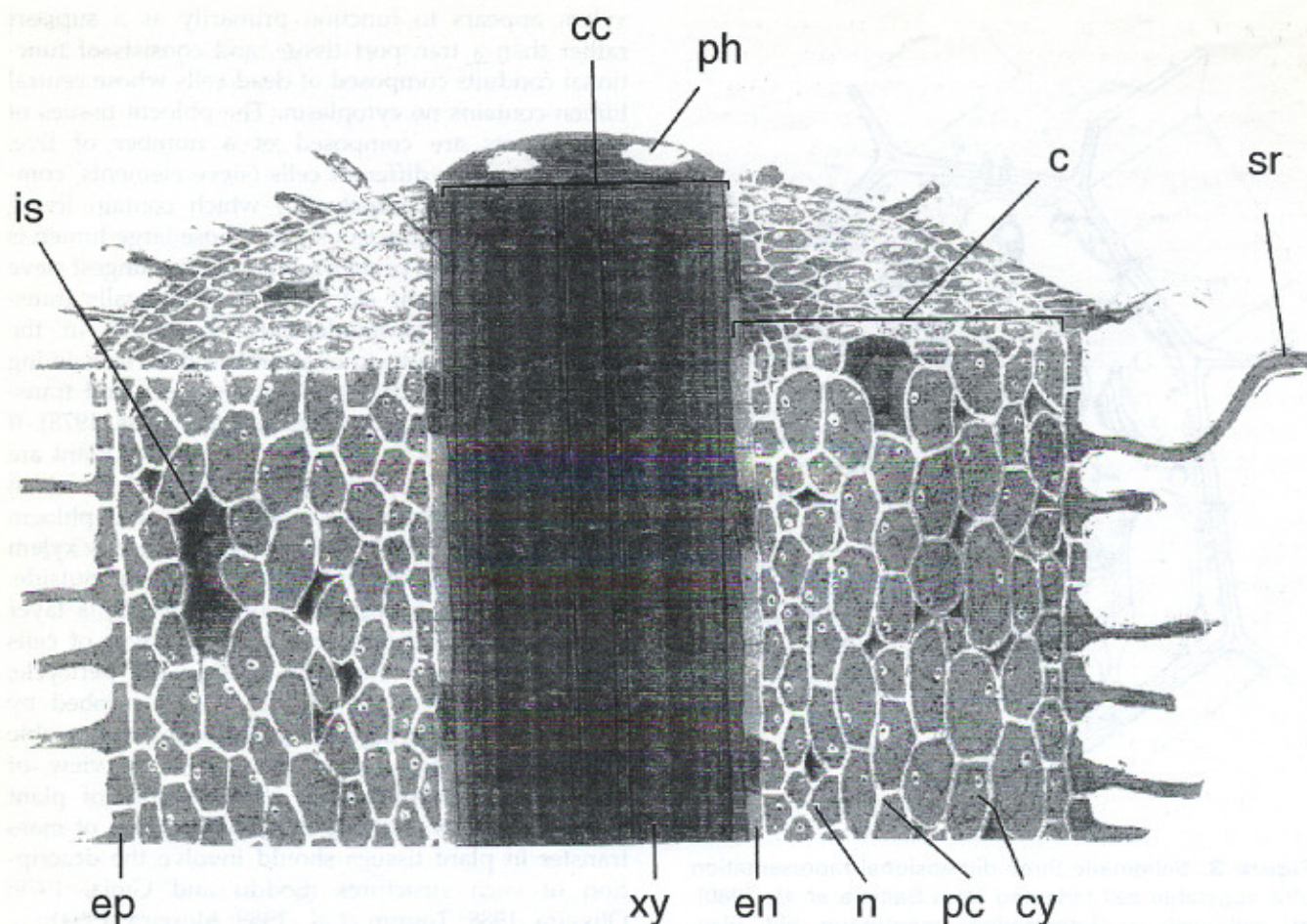


Figure 4. Schematic representation of a root tissue (adapted from Walls *et al.*, 1991). Ep, epiderm (external layer of cells); en, endoderm (upper internal layer of cells of the cortex); xy, xylem (translocation tissue responsible for upward movement of water and ions); ph, phloem (translocation tissue responsible for transport of organic compounds); n, nucleolus; pc, cell wall (rich in polysaccharides); cy, cytoplasm; c, cortex (intermediate tissue between epiderm and centre cylinder); is, intercellular space; cc, central cylinder; sr, secondary root.

Figura 4. Esquema del tejido de la raíz, tomado de Walls *et al.* (1991). Ep, epidermo (capa externa de células); en, endodermo (capa interna superior de células del cortex); xy, xilema (tejido de translocación responsable del movimiento del agua y de los iones); ph, floema (tejido de translocación responsable del transporte de compuestos orgánicos); n, núcleo; pc, pared celular (rica en polisacáridos); cy, citoplasma; c, cortex (tejido intermedio entre el epidermo y el cilindro central); is, espacio intercelular; cc, cilindro central; sr, raíz secundaria.

Fleming *et al.* (1993a) claimed that texture decay in vegetables submerged in calcium aqueous solutions in the absence of detectable microbial contamination was the result of the effect of at least two reactions of the tissues, one responsible for softening and the other for hardening; Plat *et al.* (1988) confirmed that fractions of soluble pectin and calcium pectate in processed carrot tissues are rather different from those fractions in unprocessed counterparts.

Several industrial operations are also known to bring about softening and other deleterious modifications of vegetable tissues: ripening (Bourne, 1982); freezing (Oliveira and Silva, 1992); heating (Fleming *et al.*, 1993a); plain storage (Soddu and Gioia, 1979); and brining (McFeeters and Fleming, 1989; Díez *et al.*, 1985).

Four quality factors have been tentatively considered in consumer description of foods (Bourne, 1982):

appearance, flavour, texture and nutrition. The texture of a food product is a direct consequence of the structural organization of molecules therein, and can be assessed by rheological measurements, empirical measurements, and imitative measurements (Borwanker, 1992). Instrumental measurements of vegetable texture encompass bending, compression, and deformation tests, and may be performed with such devices as hardness meters, Instron™ Universal Texture Machine systems, Kramer shear presses, load cell or strain gauge tenderometers, maturometers, Ottawa texture systems, pressure testers or penetrometers, and sonic and vibration texturometers (Holdsworth, 1979). There is a current trend towards sophisticated, non-destructive instrumental methods in the assessment of vegetable texture including transmission and scanning electron microscopy (Moreira, 1994) and ultrasonic and nuclear magnetic resonance imaging (Povey, 1989). More and more accurate and reproducible methods have also been developed relating sensory evaluation to instrumental measurements (Hard *et al.*, 1977), especially with respect to factors affecting crispness, tenderness, and juiciness. Imitative techniques are less common, and the better known method consists of imitating mechanically two bites of the mastication process (Friedman *et al.*, 1963). Even though there is experimental evidence supporting a correlation between rheology and food structure (Leung *et al.*, 1983; Holcomb *et al.*, 1992; Fleming *et al.*, 1993b), it is well established that the definition of a single rheological parameter results from an integrated perception of several contributive factors (Borwanker, 1992). It is anticipated that rheological measurements will continue to have an increasingly larger impact in the urgent quest for better quality of food products (Bourne, 1982).

Optimization

In a comprehensive review, Edgar and Himmelblau (1989) listed and discussed several advantages of implementing optimization procedures in industrial processes, for example: (i) transfer of the limiting step from the production level to the sales level by the achievement of large plant throughputs; (ii) reduction of the consumption of raw materials and energy; (iii) achievement of product quality in excess of market specifications; (iv) a decrease in losses of valuable compounds in waste streams; and (v) an increase in productivity in terms of human labour. Quantification of the influence of all production factors would permit definition of the best operating conditions for any given vegetable pickling process, but a major difficulty arises from the high number of production

factors that simultaneously play a role in processing and, hence, in the final product quality (Peres, 1995).

The solution to any optimization problem requires at least one objective function to be postulated and technical and/or economic constraints to be defined (which bound the region where an acceptable solution can be found). Examples of such functions encompass (but are not limited to): organic acid production (which acts simultaneously as a desired product and a strong inhibitor of fermentation); inventory of flavour and aroma components in the pickled product; assurance of colour and texture retention; and minimization of risks of secondary fermentations. Processing variables that can be manipulated in order to achieve optima include temperature, qualitative and quantitative characteristics of the inoculum, initial salt concentration, and degree of anaerobiosis. When mathematical models (either mechanistic or empiric in nature) are developed, truly linear behaviours seldom occur (because of factors such as parameter interactions); therefore, the objective function is prone to exhibiting more than one local optimum, thus giving rise to several mathematical solutions depending on the starting parameter estimates. Although optimal control theory has been applied successfully to fermentation processes generating high value products such as antibiotics, fermentation processes in the food industry are still conducted in a rather empirical fashion; since such processes are highly demanding in terms of processing time and equipment volume, and since aseptic precautions are a ubiquitous requirement, efforts to simulate the processes using mathematical or statistical models and define directions of improvement that will eventually lead to definition of overall optima are urged.

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