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High-Pressure Processing, Texture and Vitamin Retention in Cold-Pressed Vegetable Juices: A Review of the Evidence

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Abstract

Cold-pressed vegetable juices are sold on the promise that they have not been heated, and high-pressure processing is the technology that lets them reach a chilled retail shelf with an acceptable margin of microbial safety. This narrative review examines what the published literature says about two quality claims that accompany such products: that their body, cloud and mouthfeel resemble those of fresh juice, and that their vitamins survive the treatment. The physical chemistry is favourable. Pressure at chilled or ambient temperature leaves covalent bonds largely untouched, so ascorbic acid, carotenoids and most B vitamins are well retained immediately after treatment. The weaker point is what follows. Pectin methylesterase, polygalacturonase, polyphenol oxidase and peroxidase are often only partly inactivated, and their residual activity, together with dissolved oxygen, shapes viscosity, cloud stability, colour and vitamin C content over the weeks of chilled storage. Foliates behave differently from one vitamin to another. Evidence specific to green and low-acid vegetable juices is thin compared with that for citrus and tomato, and texture is seldom measured in ways that relate to perception. The review closes with the questions that most need answering.

Keywords: High-pressure processing, Vegetable juice, Cloud stability, Ascorbic acid, Pectin methylesterase, Chilled storage

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1. Introduction

A cold-pressed juice is made by crushing and pressing vegetables without the heat that a centrifugal extractor or a pasteuriser would add. The result tastes fresh and spoils quickly. For most of the category's short history the answer to that problem has been high-pressure processing, in which the bottled juice is held under several hundred megapascals of pressure in a water-filled vessel for a few minutes. The treatment inactivates vegetative microorganisms while the juice stays cold, and it has become the most widely used non-thermal preservation technology in the food industry (Huang et al., 2017).

Two claims travel with these products. The first concerns texture: that the juice keeps the body, the cloud and the pulpy mouthfeel of something just pressed. The second concerns nutrition: that vitamins

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which heat would have damaged are still present when the bottle is opened. Both claims rest on a sound physical argument, and both are more conditional than a label can convey. What happens to a juice in the pressure vessel is only the beginning of what happens to it before it is drunk.

This review brings together the published evidence on those two claims for vegetable juices. It considers how pressure acts on a juice, what is known about the particles and pectins that give a cloudy juice its texture, how individual vitamins respond, and how both change in chilled storage. It also marks the places where conclusions for vegetable juices have been borrowed from work on fruit.

2. Scope and Approach

The article is a narrative review of the published literature. It draws on the standard reviews of high-pressure processing and of pressure effects on plant foods, and on primary studies of tomato, carrot and mixed vegetable products that are frequently cited in those reviews. Work on orange juice is included where it supplies the only careful storage data, and is identified as such. No formal search protocol was applied and no pooled estimates are offered. The term high-pressure processing is used here for the static, in-package treatment. High-pressure homogenisation, in which juice is forced through a narrow valve, is a different operation with different effects on particles and is outside the scope.

3. How Pressure Acts on a Juice

Two principles govern the process. Pressure is transmitted uniformly and almost instantly through the product, whatever the size or shape of the package, so there is no slow-heating centre of the kind that limits thermal processing. And, following Le Chatelier's principle, pressure favours changes that reduce volume. The formation of hydrogen bonds and the disruption of ionic and hydrophobic interactions fall into that class, whereas the breaking of covalent bonds generally does not (Cheftel, 1995; Rastogi et al., 2007). Large molecules whose function depends on weak interactions, such as enzymes and membrane proteins, are therefore vulnerable. Small molecules such as vitamins, pigments and aroma compounds are largely spared (Balasubramaniam et al., 2015).

The treatment is not entirely free of heat. Compression warms water by roughly 3 °C for every 100 MPa, and oils warm more, so a juice loaded cold reaches a noticeably higher temperature at full pressure before cooling again on release (Balasubramaniam et al., 2015). The effect is modest at chilled loading temperatures, but it means that pressure and temperature can never be treated as fully separate variables when studies are compared.

Microbial targets set the commercial conditions. Vegetative bacteria, yeasts and moulds are inactivated at the pressures used commercially, while bacterial spores survive them unless heat is applied at the same time (Considine et al., 2008; Black et al., 2007). In the United States the juice regulation requires a process that achieves a 5-log reduction of the pertinent pathogen (FDA, 2001). For acidic juices that requirement can be met by pressure alone. Many vegetable juices are not acidic: carrot, beet and leafy green juices lie above pH 4.6, the conventional boundary below which spores of *Clostridium botulinum* do not grow out. Such products depend on strict refrigeration, acidification or blending with acidic fruit, and those formulation choices in turn affect both texture and vitamin stability. Figure 1 summarises the factors that the literature identifies as determining the quality of the finished juice.

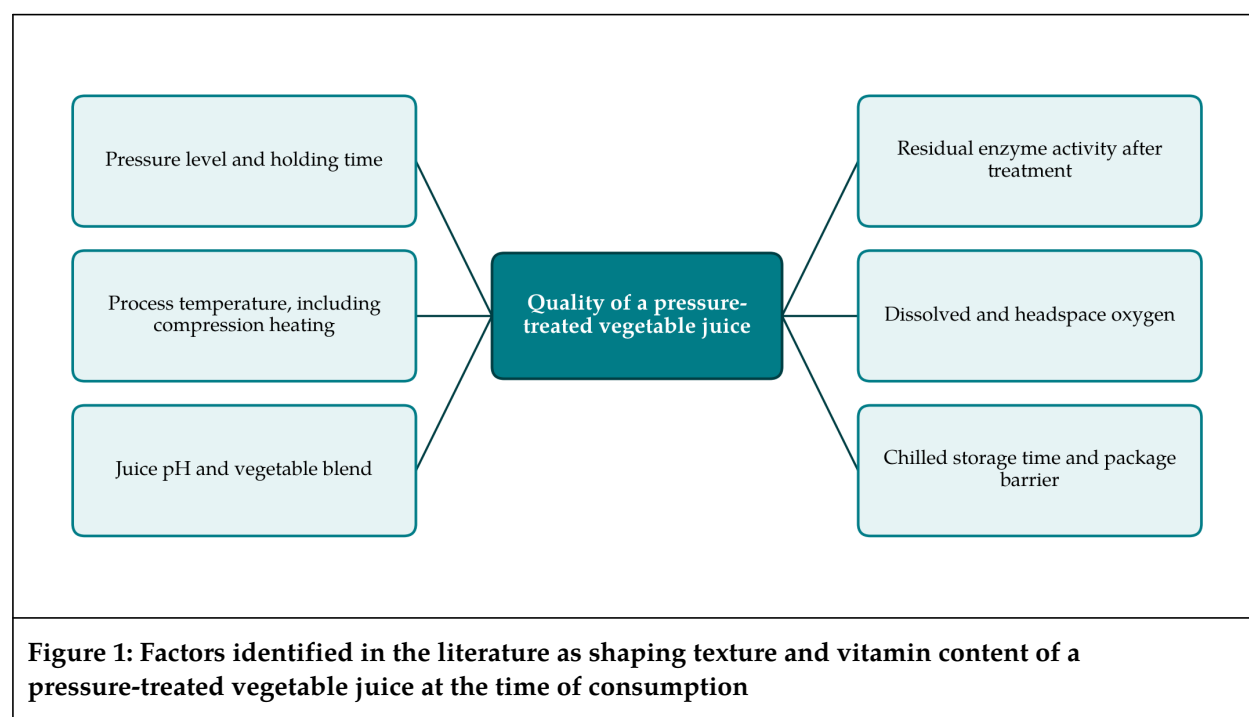
4. Texture: Cloud, Body and Mouthfeel

Texture in a juice is a matter of dispersed particles and dissolved polymers. A cold-pressed vegetable juice is a suspension of cell fragments, cell clusters and finer colloidal material in a serum that contains soluble pectin, sugars, organic acids and salts. Its apparent viscosity, its resistance to sedimentation and its perceived body depend on the volume fraction, size and shape of the particles and on the viscosity of the serum.

4.1. Particles and cell wall material

Lopez-Sanchez et al. (2011) showed for carrot, broccoli and tomato dispersions that rheological behaviour

follows from microstructure: whether cells separate intact or break, and how the fragments pack, depends on the vegetable and on the order in which mechanical and thermal steps are applied. Static pressure applied to a sealed bottle exerts no shear, so it does not reduce particle size in the way a homogeniser does. It can nevertheless alter tissue fragments. Pressure disrupts membranes, lets cell contents and enzymes mix with their substrates, and can change the hydration of cell wall material (Oey *et al.*, 2008a). In intact vegetable pieces this shows as softening or, under some conditions, firming. In a juice the corresponding changes are subtler: shifts in serum viscosity, in the tendency of particles to aggregate, and in how quickly a sediment forms.



4.2. Pectin and the enzymes that modify it

Most of the texture story is a pectin story. Pectin methylesterase removes methyl groups from the galacturonic acid backbone, leaving charged carboxyl groups. Low-methoxyl pectin produced in this way can be cross-linked by calcium ions, and it is also the preferred substrate of polygalacturonase, which cuts the chain and lowers viscosity (Sila *et al.*, 2009). The consequence depends on which enzymes remain active. In citrus juice, demethylated pectin precipitates with calcium and carries the cloud down with it. In tomato products, depolymerisation by polygalacturonase thins the serum.

Pressure does not treat these enzymes equally. Reviews of the kinetic literature agree that pectin methylesterase from several sources is highly resistant to pressure at ambient temperature, and that in tomato it is considerably more resistant than polygalacturonase (Hendrickx *et al.*, 1998; Terefe *et al.*, 2014). That selectivity has been proposed as a tool: inactivating polygalacturonase while leaving the esterase active permits demethylation without depolymerisation, and calcium cross-linking can then raise firmness or viscosity (Sila *et al.*, 2008). For a juice processor the same selectivity is a hazard, because an active esterase in a bottle that will stand for weeks invites gelation, serum separation or cloud loss, depending on the pectin and calcium present.

Careful juice studies bear this out. Bull *et al.* (2004) found pressure-treated orange juice close to fresh juice in its physicochemical characteristics, yet pectin methylesterase was not fully inactivated by the treatment they applied. Comparable enzyme data for cold-pressed carrot, beet, celery, cucumber or kale juices are scarce. The esterase and polygalacturonase of each vegetable have their own pressure and temperature stability, and juice pH shifts both their activity and their resistance, so results cannot simply be transferred from one species to another.

5. Vitamin Retention

The expectation that vitamins survive pressure treatment is broadly supported, with qualifications that differ from vitamin to vitamin. Table 1 summarises the pattern described in the sections below.

5.1. Vitamin C

Ascorbic acid is the most studied nutrient in this field, partly for its own sake and partly because it is the usual marker of processing damage. The reviews agree that pressure at chilled or ambient temperature causes little immediate loss, and that losses rise when pressure is combined with elevated temperature or long holding times (Oey et al., 2008b; Barba et al., 2012). Studies on vegetable products are consistent with this. Work on tomato and carrot purées and juices has reported antioxidant capacity and ascorbic acid after pressure treatment that compare favourably with thermally processed controls (Patras et al., 2009; Dede et al., 2007).

Table 1: Reported behaviour of selected quality attributes of vegetable and fruit juices under high-pressure processing and during subsequent chilled storage			
Attribute	Immediately after treatment	During chilled storage	Representative sources
Vitamin C	Largely retained at chilled or ambient process temperature	Declines with oxygen, residual oxidases and time	Oey et al., 2008b; Polydera et al., 2003
Folates	Depends on vitamer; some forms are pressure-labile	Oxidative loss; protected by ascorbic acid	Nguyen et al., 2003
Carotenoids	Stable; extractability may rise	Generally stable in the cold and dark	Sánchez-Moreno et al., 2006
Antioxidant activity	Similar to or above that of heated product	Follows vitamin C and phenolics	Patras et al., 2009; Dede et al., 2007
Viscosity and cloud	Little immediate change from static pressure	Governed by residual pectic enzymes and calcium	Sila et al., 2008; Bull et al., 2004
Colour	Close to fresh juice	Browning where oxidases survive	Oey et al., 2008a; Terefe et al., 2014

The degradation of ascorbic acid in juice is mainly oxidative. It needs oxygen, it is catalysed by metal ions, and in raw plant material it is accelerated by ascorbate oxidase and indirectly by peroxidase and polyphenol oxidase, whose quinone products are reduced at the expense of ascorbate. Pressure removes none of the oxygen and often leaves a share of the oxidative enzymes active (Terefe et al., 2014). Cold pressing itself incorporates air into the juice. A raw green juice may therefore enter the vessel already losing vitamin C and leave it with the cause of the loss intact.

5.2. Folates

Leafy vegetables and beetroot are valued sources of folate, and here the simple rule that small molecules are stable under pressure needs amending. Model studies from the Leuven group found that the stability of folates under combined pressure and temperature differs widely between vitamers: folic acid, the synthetic form, is robust, whereas the reduced natural forms, including 5-methyltetrahydrofolic acid, degrade more readily, and the presence of ascorbic acid protects them (Nguyen et al., 2003; Oey et al., 2008b). In a real juice the outcome will depend on the vitamer profile of the vegetables, on oxygen and on how much ascorbic acid is left. Data on folate retention in commercial-style green juices through storage are too few to support a general statement.

5.3. Carotenoids and other vitamins

Carotenoids, the provitamin A compounds of carrot and the lycopene of tomato, are little affected by pressure. Several studies have reported higher measured carotenoid contents after treatment than in the untreated product, which is read as greater extractability from a disrupted matrix and not as synthesis

([Sánchez-Moreno et al., 2006](#); [Oey et al., 2008b](#)). Whether easier extraction in the laboratory means greater bioavailability in the gut is a separate question that chemical analysis cannot settle. Thiamin, riboflavin and vitamin B6 are described in the reviews as stable to pressure at moderate temperature. For vitamin K and vitamin E in green juices the published information is sparse.

6. What Chilled Storage Adds

A pressure-treated juice is sold with a refrigerated shelf life of several weeks, far longer than the few days of an untreated cold-pressed juice. Quality at the moment of consumption is therefore decided largely in the bottle. [Polydera et al. \(2003\)](#) followed ascorbic acid in pressure-treated and thermally pasteurised orange juice across a range of storage temperatures and modelled the loss kinetically; the pressure-treated juice lost the vitamin more slowly, and temperature abuse shortened the nutritional shelf life of both. The broader review literature draws the same lesson: comparisons made on the day of processing flatter the technology, and those made at the end of shelf life are the ones that matter ([Barba et al., 2012](#); [Koutchma et al., 2016](#)).

Texture drifts over the same period. Where pectin methylesterase remains active, the degree of methylation of serum pectin falls steadily in the cold, and the visible result may be a clear layer, a weak gel or a compact sediment. Residual polyphenol oxidase and peroxidase darken the juice and consume the reducing compounds that protect colour. Packaging plays its part, since oxygen that permeates a plastic bottle wall sustains these reactions long after the dissolved oxygen present at filling has been used up. Processors respond with blends: adding lemon, apple or ginger lowers pH, which improves safety margins and slows some enzymes, and it also changes the product being studied. Much of the commercial evidence concerns such blends and not single-vegetable juices.

7. Gaps in the Evidence and Future Work

Four gaps stand out. The first is coverage. The kinetic and storage literature is dominated by orange, tomato and carrot, with a scattering of berry and apple work, while the juices that define the cold-pressed category, built on kale, spinach, celery, cucumber and beetroot, have been studied far less ([Koutchma et al., 2016](#)). The second is the measurement of texture. Studies commonly report a single viscosity value or a turbidity reading. Particle size distributions, flow curves and trained-panel descriptions of mouthfeel are seldom reported together, so the link between measured and perceived texture is weak.

The third gap is the comparison chosen. Pressure-treated juice is usually set against a heavily pasteurised control, which shows the technology at its best. Comparisons with untreated juice at the same age, and with mild modern thermal processes, would be more informative ([Knorr et al., 2011](#)). The fourth is reporting. Come-up time, initial temperature, the temperature reached under pressure, dissolved oxygen at filling and the oxygen permeability of the package are often missing, and without them studies cannot be compared or repeated ([San Martín et al., 2002](#)). Future work that reports these variables, follows enzymes and vitamins together through the full shelf life and includes low-acid green juices would fill the largest holes.

8. Conclusion

The published evidence supports a qualified version of both claims. High-pressure processing at low temperature does preserve vitamin C, carotenoids and several B vitamins through the treatment itself, and it does leave the particle structure of a cloudy juice largely as the press made it. It does not stop the enzymatic and oxidative reactions that follow, because the enzymes responsible are among the most pressure-resistant components of the juice. Texture and vitamin content at the end of shelf life depend on residual enzyme activity, oxygen, pH, storage temperature and time at least as much as on the pressure applied. For vegetable juices in particular, the evidence base is narrower than the confidence of product claims would suggest.

Conflict of interest

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