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Review

The effect of high-pressure processing on sensory quality and consumer acceptability of fruit juices and smoothies: A review

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ABSTRACT

Increasing consumer demand for high-quality, additive-free fruit and vegetable products with 'fresh-like' sensory properties has led to the development of novel 'minimal processing' technologies. As a prime example, high pressure processing (HPP) is increasingly applied as an alternative to thermal processing (TP) to maintain the properties of fresh fruit-based juices and smoothies. However, the resulting products need to be validated from a sensory standpoint. Situated within this context, this paper provides a narrative review of sensory studies focused on high pressure treated fruit juices and smoothies published in the last ≈25 years (1995 to 2021), centered around three objectives: (i) to review methods used for assessing the sensory quality, (ii) to review knowledge of the effect of HPP on sensory quality, and (iii) to understand consumers' acceptability towards these products.

Overall, most sensory studies concluded that a combination of HPP and low temperature storage preserved the sensory properties better than TP, and thereby enables the production of products with 'fresh-like' quality. Yet, most published studies employed very small panel sizes and often showed a mismatch between test type and assessors employed (for example, using consumers for analytic tests and trained assessors for affective tests), which might lead to biased results. In future research, a clearer focus on experimental conditions, proper sensory methods, and more focus on the relationship between sensory quality and consumer perception are needed to better understand the effect of HPP on the sensory quality of fruit juices and smoothies.

1. Introduction

In order to satisfy growing consumer demand for safe and high-quality food with 'fresh-like' properties, interest in minimal processing methods, such as high-pressure (HP), pulsed electric field (PEF), and ultrasound (US), has increased in recent years (Barba et al., 2017b; Ohlsson and Bengtsson, 2002). Among these, high pressure processing (HPP) has been successfully applied to a wide variety of fruit-based products such as purees (Viljanen et al., 2011), jams (Gimenez et al., 2001), and juices (Xu et al., 2015). Considering that flavor is routinely mentioned by consumers as the most important attribute in fruit-based products like juices and smoothies (Song et al., 2020, 2022), it is crucial to investigate the sensory quality and consumer perception of HPP treated fruit products before they hit the market.

Traditional thermal processing (TP) has long been the primary technology for processing juices (Ağçam, Akyıldız, and Dündar, 2018) and typical TP is related to heat treatments which are between 60 °C and 100 °C to destroy target microorganisms or enzymes which can cause undesirable changes (Awuah et al., 2007). Yet, the loss of volatile aroma compounds during such pasteurization is known to cause a reduction in quality and may result in 'cooked' flavor (Awuah et al., 2007). In contrast, HPP can achieve pasteurization at a lower temperature without heating the product; thus, it can not only address the disadvantages related to TP but also reduce the energy consumption typically associated with heating and cooling (Rastogi et al., 2007).

Fig. 1 illustrates a laboratory scale HPP equipment using different pressurizing fluids (usually water) as a medium to transmit pressures, generally from 100 to 800 MPa (Barba et al., 2017b). For HPP treatment, a food product is packed in a flexible container and transferred to the vessel where fluid is contained. Then, pressure is increased to reach the

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final pressure level through compressing the fluid by the action of a pump and a piston. After a pressure-holding period, the vessel is decompressed, and the product is removed. It is noted that different types of HP equipment exist, working in different ways. Thus, the pressure build-up can be generated by a direct (utilizing a piston, typically for lab scale machines) or an indirect (utilizing pumping water, typically for industrial machines) method (Barba et al., 2018).

HPP can partly inactivate pathogenic microorganisms and enzymes, thereby extending shelf-life. Besides, HPP affects the structure of macromolecules and flavor compounds to a lesser degree than TP (Barba et al., 2017a; Huang et al., 2017), and therefore is a promising strategy to preserve the nutritional value and sensory properties of fruit juices. As a result, the interest in HPP and its applications has been steadily increasing, especially in product categories where thermal processing performs unsatisfactorily. However, to realize the potential benefits of HPP, consumers need to accept and demand HP-treated products. It is therefore crucial that the resulting products are validated from a sensory and consumer standpoint.

To the authors' knowledge, there has not been a literature review focusing on sensory quality of HP-treated fruit juices and smoothies, which are popular beverages for which HPP has a great application potential (Caswell, 2009). To address this knowledge gap, we summarize and critically review the literature focusing on sensory methods employed to characterize the quality and acceptability of HP-treated juices and smoothies. This is followed by an account of published results, i.e., what these studies have found about the sensory quality and consumer acceptability of HP-treated products relative to fresh (untreated) or TP-treated products and to processing parameters and storage conditions. The last section then summarizes the main findings and highlights the most important directions for future research.

2. Sensory methods for evaluation of HP-treated fruit juices and smoothies

This section provides an overview of the published studies with a focus on sensory methods of HP-treated juices and smoothies. Note that the scope of this review is restricted to published studies employing human panels (i.e., studies using only electronic sensing devices and studies limited to physical/chemical measurements were not included).

Table 1 provides a broad categorization of sensory methods with exemplary references to studies using HP-treated juices and smoothies. As shown in Table 1, sensory methods can be classified into two main classes (Lawless and Heymann, 2010): analytical methods and affective methods, based on the type of information they provide. Analytical methods deal with objective characteristics of products, whilst affective methods address subjective evaluations of preference, acceptability, liking degree, etc. In line with their different objectives, analytical methods generally require the use of trained assessors, whereas affective methods should be conducted with representative consumers. Further, analytic methods include two test types: discriminative testing and descriptive testing, both containing several specific approaches to conduct the test (nature of the task/instruction). Specifically, the former asks assessors whether any perceptible difference exists between two types of products, while the latter is used to quantify the perceived intensities of sensory characteristics.

Table 2 summarizes the available literature on HP-treated juices and smoothies based on employed sensory methods. Most studies (19 out of 31) employed hedonic methods, while only ten studies used descriptive, and four studies used discriminative methods (Table 2, note that papers applying more than one method are double-counted). In terms of assessors, panels were categorized into four types: product experts, trained, semi-trained, and untrained. "Product experts" in this context are defined as panelists who have product-specific expertise (e.g., students majoring in Food Science or employees in a company producing juice), but that have not received any formal training in sensory evaluation. "Trained" and "semi-trained" assessors have received formal training but to a varying degree, whereas "untrained" are assessors without any training and specific product-related expertise. It is emphasized that training is used to get consensus on the meaning of each attribute among the assessors, and the final attribute used in the descriptive test should be precise and reliable (Lawless and Heymann, 2010). Moreover, when conducting descriptive sensory tests, it is important to determine the ideal number of trained panelists. Silva et al. (2014) pointed out that the number of evaluations will be determined based on the most critical attribute, i.e., that with the highest variance random, and the panelist number should be large enough to allow the most critical attribute to be correctly evaluated.

Correctly matching method and assessor is crucial for conducting proper sensory evaluation. For example, when conducting descriptive analysis, only trained assessors are completely qualified (Table 1), as they have been trained to use attributes in a specific, unambiguous, and non-redundant way (Lawless and Heymann, 2010). Therefore, it is

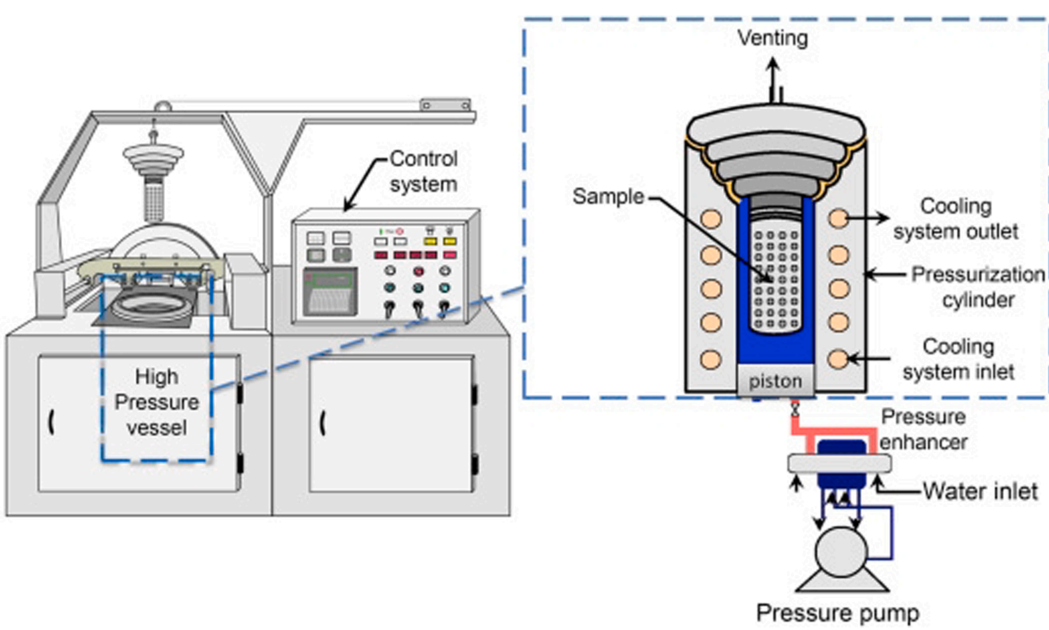

Fig. 1. Schematic representation of a laboratory scale high pressure processing equipment, from (Barba et al., 2017b). Reprinted with permission from Elsevier.

Table 1
Sensory evaluation methods employed for analysis of high pressure treated juices and smoothies with exemplary references.

Type of test	Class	Objective	Characteristics of the assessor panel	Method	Task/instruction	Exemplary reference
Analytic	Discriminative testing	Are samples perceptibly different in any way?	Screened for sensory acuity, sometimes trained	Triangle test	Choose the odd sample or report which two samples are similar from three given samples.	Hurtado et al. (2015)
				Paired comparison test	Determine which of two samples differs in a sensory attribute.	Ma et al. (2010)
				Duo-trio test	Choose the sample from a set of three samples (whereby one sample is marked as reference) which is the same as the reference.	Ma et al. (2010)
Analytic	Descriptive testing	How do samples differ in specific sensory attributes?	Screened for sensory acuity and motivation, trained or highly trained	Category scale	Choose the alternative that best represents their sensation intensity to an attribute in a pointed line.	Daoudi et al. (2002)
				Line scale	Make a mark or slash on a continuous line to indicate the intensity of an attribute.	Laboissière et al. (2007)
				Magnitude estimation	Assign numbers for sensation magnitudes in proportion to how strong the sensation seems to be.	Parish (1998)
Affective	Hedonic testing	How is the impression towards samples or how well are they accepted?	Screened for product usage, untrained	Hedonic scaling	Consumer acceptance is scored on a scale from extremely like to extremely dislike on each end.	Keenan et al. (2011)
				Ranking	Order the products from least liked to most liked.	Castellari et al. (2000)

generally not advisable to use untrained assessors for analytical tests or trained assessors for affective tests, because the reliability of data from an untrained panel would be questionable, whilst a trained panel could not be representative of the average consumers. However, as seen in Table 2, several studies show in fact a mismatch between methods and assessors. A “mismatch” is defined as either using a trained panel to score their total impression and acceptability, or untrained consumers to assess the intensity of sensory attributes. This is most often occurring in studies employing affective methods, which in most cases (10 out of 19 studies) used small panels of experts or trained assessors to evaluate the products’ acceptability rather than actual consumers. By contrast, studies employing discriminative and descriptive tests employed the right type of assessors in most cases (Table 2).

Relatedly, current recommendations for hedonic tests require assessors to be recruited among representative consumers and the sample size to be in the 50–100 subjects’ range, depending on the size of differences between the products (Mammasse and Schlich, 2014). Only one study (Inada et al., 2018) out of those reviewed in Table 2 met that reccomendation, while most studies report data based on 10–20 subjects, hence far below standards of good practice. These two issues combined (mismatch plus small sample size) suggest that available findings regarding consumer acceptability of HP-treated products should be treated with caution.

Table 2 further contains several important indications about the methods used to evaluate the sensory quality of HP-treated juices and smoothies: types of method and panel, record task, sensory profile which can be described by appearance, aroma, taste, and mouthfeel. Generally, the more attributes employed in sensory evaluation, the more comprehensive the sensory profile will be. However, one notable finding here was the definition (or lack thereof) of each attribute. For example, the process of sensory lexicon development and the reference associated with each attribute of HP-juices during panel training was not clearly (or not at all) explained in most of the reviewed studies. Besides, some sensory attributes appeared ambiguously categorized; for instance, “sweetness” was not clearly categorized as a taste attribute (e.g., Daoudi et al., 2002; Chang et al., 2017; Zheng et al., 2014; Huang et al., 2015; Rios-Corripio et al., 2020). The lack of precision in defining sensory attributes is a limitation of the reviewed literature. Without a clear reference, it is hard to fully understand sensory changes of HP-treated juices and smoothies, and whether the information gained can be extended to other similar products or is specific to that study only.

3. Experimental conditions pertaining to HP processing and storage

There are three main parameters, pressure level, holding time, and initial temperature, known to affect the effectiveness of HPP to inactivate microorganisms, enzymes, and bacterial spores (Oey et al., 2008). While small molecules like aroma compounds are not directly affected by pressure (Oey et al., 2008), the potential pressure-induced activation of enzymes and other chemical reactions associated with HPP may still result in flavor changes. Hence, it is of interest to assess what the literature reports about what sensory properties are affected and to which degree.

Table 3 reports the products, experimental conditions, and design as well as main results in the available literature on HP-treated juices and smoothies. As shown in Table 3, the range of these parameters is rather wide: 200 to 900 MPa for pressure, 2 to 60 °C for temperature, and 1 to 20 min for holding time.

For pressure, 27 out of 31 studies focused on the interval 400–600 MPa. This reflects the fact that pressure levels above 400 MPa inactivate vegetative cell, while the inactivation of pathogenic microbes varies considerably (Niakousari et al., 2018). In addition, pressure levels above 400 MPa are known to cause protein unfolding and inactivation/activation of enzymes, thus resulting in several chemical and physical changes that may have effect on sensory quality (Knorr et al., 2010). Temperature is another crucial parameter, and 27 out of 31 studies reported temperature parameters (Table 3). As suggested by Patterson (2005), a combination of intermediate temperatures (20–50 °C) with increased pressure is a practical way to overcome the problem of pressure-resistant strains of vegetative cells. Ferrari et al. (2010) also pointed out that intermediate processing temperature (25–50 °C) is the parameter controlling the effect of HPP (400–600 MPa during 5 or 10 min) on pomegranate juice appearance. Therefore, considering the importance of pressure and temperature, it is recommended to show all parameters (rather than just pressure level and time) in order to elucidate the comprehensive impact of HPP parameters on the final product quality.

HPP at room temperature does not necessarily result in the inactivation of pressure resistant bacterial spores and enzymes, which may potentially cause the spoilage of HP-treated products during storage. Indeed, major changes in the chemical composition and quality of strawberry purée and juice occurred during storage, not during HP

Table 2
Sensory methods for evaluating high pressure treated fruit juices and smoothies. The table lists papers firstly ranked by method type (discriminative, descriptive, and hedonic). Within each method type, papers are ranked by publication year.

Method	Formulation of samples	Panel	Sensory profile	Record/Score	Reference
Discriminative	Cantaloupe juice	10 testers with sensory evaluation experience	Aroma	Record whether the aromas of two samples in each pair were different or not by using paired comparison test and duo-trio test.	Ma et al. (2010)
Discriminative	Smoothies (apple juice, orange juice, strawberry, apple, banana)	6 trained	Flavor	Choose the odd sample in a triangle test by focusing on the possible off-flavor, in particular, cooked-fruit "pressurized-like" flavors.	Hurtado et al. (2015)
Discriminative	Watermelon juice	30 untrained	Appearance, aroma, taste	Observe, smell, and taste the samples to find the odd sample.	Aganovic et al. (2016)
Discriminative and descriptive	Orange and an orange-lemon-carrot juice	6–11 trained for a triangular test; at least 6 trained for descriptive analysis	Odor and taste for discriminative method Color, odor, taste, harmony for descriptive method	The effect of HPP on odor and taste was analyzed using the "forced choice" technique in a triangular test. 9-point scale (9 = perfect or optimal, 8 = typical or without defects, 7 = typical or with slight deviations, 6 = noticeable deviations, 5 = noticeable detractions or light defects, 4 = distinct defects, 3 = strong defects, 2 = very strong defects, 1 = completely changed)	Fernández García et al. (2001)
Descriptive	Orange juice	15 trained	Flavor	150 mm line which had a 'no difference' anchor point on the left end and a "large difference" anchor point on the right end of the line	Parish (1998)
Descriptive	White grape juice	8 experts	Fresh fruit aroma, cooked fruit aroma, grass aroma, sweetness, acidity, off-flavor	0–9 category scale (from very weak to very strong)	Daoudi et al. (2002)
Descriptive	Yellow passion fruit juice	17 trained	Appearance (characteristic passion fruit juice color, presence of suspended particles, turbidity, phase separation), aroma (natural passion fruit, artificial passion fruit, acid, sweet, cooked, fermented), flavor (natural passion fruit, artificial passion fruit, acid, sweet, cooked, fermented), mouthfeel (astringency), consistency	Unstructured 9 cm line scale, anchored with the words "weak", "little" or "absent" and "strong" or "much"	Laboissière et al. (2007)
Descriptive	Smoothies (strawberries, apples, apple juice, bananas, oranges)	12 trained	Appearance (pink color, fresh, turbidity), aroma (apple, orange, banana, strawberry, acid, fresh), flavor (apple, banana, acid, fresh, overall), texture/mouthfeel (graininess, viscosity, separation)	15 cm line scale ranging from low intensity (0 cm) corresponding to the word anchor "none" to high intensity (15 cm) corresponding to the word anchor "strong"	Keenan et al. (2012)
Descriptive	Smoothies (apples, strawberries, bananas, oranges)	6 trained	Appearance (coral color, rust-brown color), odor (odor intensity, banana, strawberry, cooked), taste and flavor (sweet, acid, bitter, banana, strawberry and cooked), mouthfeel (sliminess, grittiness), overall sensory quality	Non-structured scoring scale (0 = absence of the descriptor, 10 = a high intensity of the descriptor)	Picouet et al. (2016)
Descriptive	Smoothies (strawberries, oranges, apples, bananas, black grapes, blackberry, gooseberries, white grapes, limes)	6 trained	Appearance (darkness, turbidity), odor (intensity, fresh fruit, cooked fruit, strawberry/red fruit, banana), flavor (intensity, fresh-fruit, cooked fruit, strawberry/red fruit, banana, acid taste), mouthfeel texture (sliminess, grittiness), overall sensory quality	Non-structured scoring scale (0 = the absence of the descriptor, 10 = a high intensity of the descriptor)	Hurtado et al. (2017)
Descriptive	Strawberry purée and juice	7 trained	Color intensity, color saturation (pure red to impure brown/grey), viscosity, strawberry odor, strawberry flavor intensity, strawberry flavor typical, sweet taste, sour taste, fresh flavor, ripened flavor, oxidized flavor, off-flavor	Continuous non-structured scale (from 1 to 9)	Aaby et al. (2018)
Descriptive	Mango juice	10 trained	Aroma (fruity, sweet, floral, fresh, grassy, sweaty, rosin)	7-point intensity scale in 0.5 increments from 0 to 3	Zhang et al. (2019)
Descriptive and hedonic	Navel orange juice	10 trained and 30–40 untrained	Appearance (color), aroma (sweetness, aged, artificial, fermented, overall strength of orange aroma), flavor (sourness, sweetness, processed, bitterness, overall strength of orange	100 mm line scale anchored at 0 mm with "weak'' and at 100 mm with "strong'' for sensory attributes, while a 9-point hedonic category scale (1 =	Baxter et al. (2005)

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Table 2 (*continued*)

Method	Formulation of samples	Panel	Sensory profile	Record/Score	Reference
			flavor), aftertaste (acidity, sourness, bitterness, duration), acceptability	dislike extremely, 9 = like extremely) for consumer acceptability	
Hedonic	Tomato juice	7 trained	Natural taste, cooked taste, off-taste	1–9 category scale, naturalness (1 = taste very similar to the fresh one, 9 = taste very different from the fresh one), cooked (1 = absent, 9 = burnt), off-taste (1 = absent, 9 = strong)	Porretta et al. (1995)
Hedonic	Grape juice	12 trained	Aroma, taste	Rank the six samples according to overall aroma and taste, from less preferred (sixth) to most preferred (first).	Castellari et al. (2000)
Hedonic	Orange juice	7 trained	Flavor, impression	9-grade hedonic scale	Polydera et al. (2003)
Hedonic	Navel orange juice	6 trained	Flavor, impression	9-grade hedonic scale	Polydera et al. (2005)
Hedonic	Smoothies (strawberries, apples, concentrated apple juice, bananas, oranges)	15 untrained	Acceptability	6 cm scale with endpoints of 0 (unacceptable) and 6 (very acceptable)	Keenan et al. (2011)
Hedonic	Peach (Prunus persica) juice	10 trained	Color, turbidity, aroma, flavor, impression	Hedonic scale (1 = dislike extremely, 5 = like extremely)	Rao et al. (2014)
Hedonic	Litchi juice	15 semi-trained	Odor, sweetness, acidity, acceptability	9-point hedonic scale (9 = like very much, 1 = dislike very much)	Zheng et al. (2014)
Hedonic	Sugarcane juice	20 taste-sensitive	Appearance, odor, sweetness, flavor, acceptability	The scale of 1–10 (1 indicating the lowest and 10 the highest level of acceptance)	Huang et al. (2015)
Hedonic	Apple juice	4 experienced in sensory evaluation but without training	Perception	9-point hedonic scale test (1 = extremely dislike, 9 = extremely like)	Juarez-Enriquez et al. (2015)
Hedonic	Yellow sweet pepper and orange juice blend	20 trained	Color, appearance, flavor, mouthfeel, acceptability	9-point hedonic scale (1 = dislike extremely, 2 = dislike very much, 5 = neither like nor dislike, 8 = like very much, 9 = like extremely)	Xu et al. (2015)
Hedonic	Aloe vera-litchi juice	10 trained	Color, aroma, consistency, taste, aftertaste	9-point hedonic scale (1 = dislike extremely, 9 = like extremely)	Swami Hulle and Srinivasa Rao (2016)
Hedonic	White grape juice	20 trained	Bitterness, sweetness, aroma, acidity, acceptance	The scale of 1–10 (1 indicating the lowest and 10 the highest level of acceptance)	Chang et al. (2017)
Hedonic	Elephant apple juice	25 untrained	Odor, taste, acceptability	Acceptability as a composite of odor and taste was estimated using a scale ranging from 0 to 9 (9 = excellent, 8 = very good, 7 = good, 6 = acceptable, 0–5 = poor (first off-odor, off-taste development))	Nayak et al. (2017)
Hedonic	Whey-based sweet lime juice	15 semi-trained	Taste, color, aroma, flavor, after taste, appearance, mouth feel, acceptability	9-point hedonic scale (1 = extremely dislike, 9 = extremely like)	Bansal et al. (2018)
Hedonic	Jabuticaba (Myrciaria jaboticaba) juice	80 untrained	Impression, aroma, taste, appearance, texture	9 cm unstructured scale (0 = dislike extremely, 4.5 = indifferent, 9 = like extremely)	Inada et al. (2018)
Hedonic	Pêra-Rio orange juice	49 untrained	Color, aroma, flavor, texture, overall impression	9-point hedonic scale (9 = like extremely, 5 = neither like nor dislike, 1 = dislike extremely)	Mastello et al. (2018)
Hedonic	Pomegranate beverage	20 untrained	Appearance, color, aroma, sweetness, flavor, acceptability	9-point hedonic scale	Rios-Corripio et al. (2020)
Hedonic	Mixed juice (cashew apple, acerola, and melon)	30 untrained	Appearance, aroma, flavor, texture, aftertaste	3-point structured scale (1 = low, 2 = medium, 3 = high)	Martins et al. (2022)

processing (Aaby et al., 2018). Therefore, cold storage is needed to preserve the quality of the treated products. Accordingly, 24 out of 31 reported studies (Table 3) usually refrigerated juices and smoothies after processing. In line with this, Swami Hulle et al. (2016) reported that the shelf-life of HP treated aloe vera-litchi mixed beverage stored at 4, 15 and 25 °C was up to 110, 30, and 5 days respectively, according to both physicochemical and sensory based shelf-life determination. Furthermore, orange juice stored at 8 °C was found to have worse sensory quality than juice stored at 4 °C (Parish 1998). Finally, apple juices stored at 4 °C were preferred over those stored at 20 °C during 34 days of storage due to better retention of taste, flavor, and aroma (Juarez-Enriquez et al., 2015).

Seven out of 33 studies either did not mention storage temperature or reported it in an unclear way. One possible reason for this was that sensory tests were done very shortly after processing (thus rendering storage time less relevant). For example, sensory evaluation was conducted just after treatments in the study of Change et al. (2017), Xu et al. (2015), and Rao et al. (2014). Alternatively, some studies used commercial products rather than experimental samples. Laboissière et al. (2007) compared HP-treated yellow passion fruit pulp to five commercial TP-juices regarding sensory properties, without reporting storage conditions or production time and age of the commercial juices.

4. Effect of HPP on sensory quality and consumer acceptability of juices and smoothies

This section elaborates on the sensory qualities of HP-treated products relative to either fresh (untreated) and/or TP-treated products (see 4.1), and specific sensory changes in HP-treated products about different storage or pressure conditions (see 4.2). Results are reviewed concerning different sensory modalities (appearance, aroma, taste, and mouthfeel) by the discriminative and descriptive methods and overall acceptability

Table 3
Sensory studies of high pressure treated fruit juices and smoothies. The table lists papers firstly ranked by method type (discriminative, descriptive, and hedonic). Within each method type, papers are ranked by publication year. HP = High pressure, TP = thermal processing.

Method	Products	Treatment conditions	Experiment design (comparing treatments & storage)	Main results	Reference
Discriminative	Cantaloupe juice	400 and 500 MPa for 20 min at 22 °C	Untreated juice. Stored at 2–10 °C and evaluated within 2 h after the end of pressure treatment.	There was no significant aromatic difference between HP- and untreated melon juice samples, as well as between the samples treated at 400 and 500 MPa.	Ma et al. (2010)
Discriminative	Fruit smoothies*	350 MPa for 10 min at 10 °C; 450 MPa for 5 min at 10 °C; 600 MPa for 3 min at 10 °C	TP-smoothie (at 85 °C for 7 min). Stored at 4 °C for 48 h.	TP- and HP-treated samples (600 MPa) were clearly different from others and were rejected due to flavor alterations. The sensory panel did not discriminate between flavors in smoothies pressurized at 350 and 450 MPa.	Hurtado et al. (2015)
Discriminative	Watermelon juice	600 MPa for 5 min at room temperature	Untreated juice, TP-juice (at 74 °C for 45 s), pulsed electric field treatment (11 kV/cm, 175 kJ/kg). Stored at 3 °C for 12 days and evaluated at 0 and 12 days.	The significant difference between untreated and processed samples was determined immediately after the treatment, as well as among processed samples alone either immediately after the treatment or at the end of the shelf-life.	Aganovic et al. (2016)
Discriminative and descriptive	Orange juice and an orange-lemon-carrot juice	800 and 500 MPa for 5 min	Untreated juice. Stored at 4 °C for 21 days, and evaluated on 0, 7, 14, and 21 days.	For orange juice, the sensory quality of HP-juice (at 500 MPa) was closer to untreated juice, and defects in odor and aroma were greater in HP-juice (at 800 MPa). Mixed HP-juice at 800 MPa showed a slight, but a significant defect in odor and flavor towards more intense carrot aroma, metallic-bitter, and less harmonious.	Fernández et al. (2001)
Descriptive	Orange juice	700 MPa for 60 s at 31 °C; 500 MPa for 90 s at 25 °C; 500 MPa for 90 s at 50 °C; 500 MPa for 90 s at 60 °C	Untreated juice, TP- juice (at 98 °C for 10 s and 75 °C for 10 s). Stored at 4 and 8 °C for 16 weeks, and evaluated at 0, 4, 8, and 16 weeks.	Although differences between HP- and untreated-juices were significant, the flavors of the two pressure-treated juices (without added heat) were significantly closer to that of untreated-juice than flavors of TP-juice.	Parish (1998)
Descriptive	White Grape Juice	500 MPa for 10 min at 2 °C	Untreated juice. Stored at 4 °C for 60 days and evaluated on the 1st, 30th, and 60th day of storage.	No sensory changes were noted on the first day between untreated and treated samples. On the 60th day, HP-juice displayed stable sweetness, acidity levels, less grass aroma, off-flavor, and cooked fruit aroma, but a slight decrease in fresh fruit aroma.	Daoudi et al. (2002)
Descriptive	Yellow passion fruit juice	300 MPa at 25 °C for 5 min	Untreated, five commercial TP juice	The only significant difference between HP- and untreated juice was color attributes, and all samples (untreated and processed) were very similar regarding the attribute sweet aroma.	Laboissière et al. (2007)
Descriptive	Fruit smoothies*	450 MPa for 5 min at 20 °C or 600 MPa for 10 min at 20 °C	Untreated smoothie, TP-smoothie (P_{70}** ≥10 min). Stored at 4 °C for 30 days, and evaluated at 0, 15, and 30 days.	Differences between the processes were small, except for the pink color that was perceived significantly higher in untreated samples than their processed counterparts by pasteurizing.	Keenan et al. (2012)
Descriptive	Fruit smoothies*	350 MPa for 5 min at 9–10 °C	Untreated smoothie, TP-smoothie (at 80 °C for 7 min). Stored at 4 °C for 21 days and evaluated at 0, 7, 14, 21 days.	HPP better preserved the original color and flavor of the multi-fruit smoothies, and the overall sensory quality of HP-smoothie was higher than that of the mild TP-smoothie.	Picouet et al. (2016)
Descriptive	Fruit smoothies*	350 MPa at 10 °C for 5 min	Untreated smoothie, TP-smoothie (at 85 °C for 7 min). Stored at 4 °C for 28 days, and evaluated at 1, 7, 14, 21, and 28 days.	HP-smoothie provided 'fresh-like', free of cooked-fruit flavor, for at least 14 days at 4 °C, although sensory stability was lower than TP-smoothie. In HP-smoothie, the loss of fresh fruit flavor and reduced sliminess signed sensory deterioration.	Hurtado et al. (2017)
Descriptive	Strawberry purée and juice	400, 500 and 600 MPa at 20 °C for 3 min	Untreated juice, TP-juice (at 85 °C for 2 min). Processed samples stored at 6 °C and evaluated all samples after 35 days	For the processed juices, concurring scores were seen for most attributes, except for the juice treated at 600 MPa, having a higher viscosity than the other juices.	Aaby et al. (2018)
Descriptive	Mango juice	200, 400, and 600 MPa for 15 min at room temperature	Untreated juice, TP-juice (at 80 °C for 3 min). Stored at − 80 °C until further use within two weeks	HP-juice received a very close flavor score to the untreated juice compared with TP-juice. HP-juice was closer to untreated juice relatively, though untreated mango juice was mostly favorable.	Zhang et al. (2019)
	Navel orange juice				

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Table 3 (*continued*)

Method	Products	Treatment conditions	Experiment design (comparing treatments & storage)	Main results	Reference
Descriptive and hedonic		600 MPa for 60 s at ambient temperature (18–20 °C)	Untreated juices and TP-juice (at 85 °C for 25 s). All treated samples were stored at − 20, 4 and 10 °C and all samples were evaluated at baseline (2 days after processing) and on 0, 1, 2, 4, 8, and 12 weeks.	HP-juice had odor and flavor profiles comparable with those of untreated (at −20 °C) and TP-juice (at 4 °C). HP- and TP-juices (at 4 °C) had marginally superior aftertaste than untreated (at −20 °C). Yet, HP-juice (at 10 °C) was inferior to untreated, TP-and HP-juice (at 4 °C).	Baxter et al. (2005)
Hedonic	Tomato juice	500 MPa for 3 min, 700 MPa for 6 min, 900 MPa for 9 min	TP-juice at 98 °C for 15 min	Juices treated at any value of input process variables proved to be absolutely inedible owing to a strong rancid taste, which made it impossible to perform sensory evaluations.	Porretta et al. (1995)
Hedonic	Grape juice	600 MPa for 5 min at 20 °C and 50 °C with or without enzymes addition	Grape juice with and without enzyme addition as control. Stored at 5 °C for 27 days and then evaluated.	The HP-juice with enzyme addition was mostly preferred. HP with an initial temperature of 50 °C did not improve the sensory quality compared with that with 20 °C.	Castellari et al. (2000)
Hedonic	Orange juice	500 MPa at 35 °C for 5 min	Untreated juice, TP-juice (at 80 °C for 30 s). Stored at 0, 5, 10, and 15 °C for at least 1 or 2 months depending on the type of package (give types) used.	For the same storage period, HP-juice was judged of superior sensory quality than the TP-juice irrespective of the type of package, retaining more the flavor of the untreated reconstituted orange juice.	Polydera et al. (2003)
Hedonic	Navel orange juice	600 MPa for 4 min at 40 °C	Untreated juice, TP-juice (at 80 °C for 60 s). Stored at 0, 5, 10, 15 and 30 °C for 100 days and evaluated at 0, 20, 40, 60, 80 and 100 days.	The flavor and aroma of untreated juice were retained immediately after HPP. The sensory quality of HP-juice was judged superior to the TP-juice during storage at all temperature conditions tested.	Polydera et al. (2005)
Hedonic	Fruit smoothies*	450 MPa for 1, 3, or 5 min at ambient temperature	Untreated smoothie, TP-smoothie (P_{70}** ≥10 min). Stored at 4 °C for 30 days, and evaluated at 1, 10, 20, and 30 days.	No significant effect was observed between processing treatments. The sensory acceptability of the smoothie was significantly affected by storage. A significant difference in acceptability was observed only between the 1st and 30th days of storage.	Keenan et al. (2011)
Hedonic	Peach (Prunus persica) Juice	600 MPa for 10 min at room temperature (25 °C)	Untreated juice, TP-juice (at 90 ± 2 °C for 1 min). Sensory evaluation was just after processing.	All attributes of HP-juice exhibited similar scores to untreated juice. HP-juice had greater typical fresh peach aromas than TP- and untreated juice.	Rao et al. (2014)
Hedonic	Litchi juice	500 MPa for 2 min at ambient temperature (~25 °C)	Untreated juice, TP-juice (at 95 °C for 1 min). Stored at 4 °C for 4 weeks and evaluated after processing and after 4 weeks storage.	No significant differences were detected by the Panelists between fresh and HP-juice in terms of odor, acidity, sweetness, and overall acceptability.	Zheng et al. (2014)
Hedonic	Sugarcane Juice	200, 400, or 600 MPa for 6 min at 20 °C	Untreated juice, TP-juice (at 97 ± 1 °C for 60 s). Stored at 4 °C	The HP-juice showed a decrease in acceptance score of color, aroma, and sweetness with the increase in processing pressure; however, these scores were better than those of the TP-juice.	Huang et al. (2015)
Hedonic	Apple juice	430 MPa for 7 min at 20 °C	Treated juices with different storage times and temperatures. Stored at 4 and 20 °C for 34 days, and evaluated at 1, 6, 13, 20, 27, and 34 days.	The general perception was that HP-juice preserved its main attributes during the shelf-life period. The juice stored at 4 °C, was preferred over that stored at 20 °C due to better retention of taste, flavor, and aroma.	Juarez-Enriquez et al. (2015)
Hedonic	Yellow sweet pepper and orange juice blend	550 MPa for 5 min at ambient temperature (≈ 25 °C)	Untreated juice, TP-juice (at 110 °C for 8.6 s). The sensory evaluation was after treatments.	The HP-juice exhibited great color, flavor, and appearance, which could be barely distinguished from the untreated ones, and its mouthfeel and overall acceptability were closer to untreated ones.	Xu et al. (2015)
Hedonic	Aloe vera-litchi mixed beverage	600 MPa at 56 °C for 15 min	Untreated juice, TP-juice (at 95 °C for 5 min). Stored at 4 °C for 120 days and evaluated at 0, 15, 30, 45, 60, 70, 80, 90, 100, 110 and 120 days.	The taste and aroma of samples reached an unacceptable level in HP-juice. The bitter aftertaste was noted after the 100 days of storage in HP-juice.	Swami Hulle et al. (2016)
Hedonic	White grape juice	300 or 600 MPa for 3 min at 20 °C	Untreated juice, TP-juice (at 90 °C for 60 s), and the sensory evaluation was after treatments.	The HP-juice showed a slight decrease in acidity, aroma, and sweetness with an increase in pressure; however, these scores were better than those of the TP-juice. A similar score for overall acceptance for the HP- and untreated juices was provided.	Chang et al. (2017)
Hedonic	Elephant apple juices	600 MPa for 5 min at 35 °C	Untreated juice, TP-juice (at 80 °C for 60 s). Stored 4 °C for 60 days and evaluated	HP-juice had better sensory properties (aroma and taste) than untreated juice.	Nayak et al. (2017)

(continued on next page)

Table 3 (*continued*)

Method	Products	Treatment conditions	Experiment design (comparing treatments & storage)	Main results	Reference
			at 0, 1, 2, 5, 10, 20, 30, 40, 50 and 60 days.		
Hedonic	Whey-based sweet lime beverage	500 MPa for 10 min at 25 °C	Untreated juice, TP-juice (at 90 °C for 60 s). Stored at 4 °C for 120 days and evaluated at 0, 20, 40, 60, 80, 100, and 120 days of storage.	Compare to untreated and TP-juice, HP-juice had an acceptable flavor and color that sustained the overall acceptability till 120 days.	Bansal et al. (2018)
Hedonic	Jabuticaba (Myrciaria jaboticaba) juice	350 MPa for 7.5 min	Untreated juice	HPP did not affect acceptance of overall impression, taste, acceptance, texture, except for aroma, whose score decreased 10% due to pressurization.	Inada et al. (2018)
Hedonic	Pêra-Rio orange juice	520 MPa at 60 °C for 360 s	Untreated juice, TP-juice (at 95 °C for 30 s)	Sensory acceptance allowed noticing differences mainly in flavor but not in the aroma of HP- and TP-juice and the untreated orange juice was the most accepted.	Mastello et al. (2018)
Hedonic	Pomegranate juice	500 MPa for 10 min, 550 MPa for 10 min, and 600 MPa for 5 min	Untreated juice, TP-juices (at 63 °C for 30 min and 72 °C for 15 s, respectively). Stored at 4 °C and evaluated at the end of storage (42 days).	Significant differences were observed only with the appearance and color of untreated and processed beverages. All TP- and HP-juice were well sensory accepted.	Rios-Corripio et al. (2020)
Hedonic	Mixed juice (cashew apple, acerola, melon)	500 MPa for 5 min, and 520 MPa for 2 min	Untreated juice, TP-juices (at 90 °C for 1 min). Stored at 4 °C for 0, 4 and 28 days.	Consumers perceived HP-juices as like the untreated juice during the 28 storage days. TP-juices had lower intensity of the fresh attribute than HP- and untreated juices.	Martins et al. (2022)

* Formulations of the fruit smoothies are given in Table 2.
** A P_{70}-value expresses the effect achieved by the completed non-isothermal heat treatment on the inactivation of *L. monocytogenes* as the equivalent time in minutes at 70.

by the hedonic method.

4.1. Sensory quality of HP-treated juices and smoothies compared to fresh and TP-treated products

There are 11 (out of 31) analytical studies that considered the sensory quality of HP-treated juices and smoothies products compared to untreated and TP-treated products (Table 3). The general tendency uncovered in these studies is that HP-treated products are closer to fresh (untreated) ones than to TP-ones for the intensity of and acceptance for most sensory attributes.

Appearance: in the study from Laboissière et al. (2007), the discriminative method was used to differentiate untreated and HP-treated yellow passion fruit juice from commercial TP-juice in terms of suspended particles, turbidity, phase separation. Yet, color was the only significant difference between HP- and untreated samples, where the former was similar to two commercial TP-juices. Likewise, HP- and TP-treated strawberry juices obtaining identical scores of color intensity and saturation (Aaby et al., 2018).

Aroma and taste: no significant difference in aroma was found between untreated and HP-treated cantaloupe juice (Ma et al., 2010) and in floral aroma, sour aroma, fruity aroma, sweet and grassy aroma of mango juice (Zhang et al., 2019). Hurtado et al. (2015) found that two HP-treated smoothies were not discriminated from fresh smoothies regrading to "fresh-like" fruit flavor, but TP-smoothie was characterized by a cooked-fruit flavor. Similarly, Laboissière et al. (2007) showed that untreated and HP-treated yellow passion fruit juice was differentiated from commercial TP-juices in terms of natural passion fruit aroma and flavor, artificial passion fruit aroma and flavor, acid aroma and flavor, sweet taste, cooked aroma, and flavor, and fermented aroma and flavor. Yet, no significant difference in the sweet aroma was found among untreated and processed (TP and HPP) juices. Aaby et al. (2018) also reported that the score of HP-treated strawberry juices concurred with that of TP-juice regarding strawberry odor and flavor, sour taste, sweet taste, fresh flavor, ripened flavor, oxidized flavor, and off-flavor. By contrast, TP-mango juice had the minimum intensity of sweet and grassy aroma, according to Zhang et al. (2019), but HPP gave mango juice a more intense rosin smell.

Mouthfeel: mouthfeel attributes can be either related to the rheology of the product and/or the force of breakdown (such as viscosity) or chemically induced tactile sensations (such as astringency). According to Laboissière et al. (2007), the astringency and mouthfeel of untreated and HP-juices were different from those of commercial TP-juices, whereas HPP caused no significant modifications in the juices' mouthfeel.

Acceptability: as mentioned earlier, findings regarding acceptability should be treated with caution due to low sample size and inappropriate use of assessors as identified earlier. Four studies reported a general trend: acceptability of HP-juice was on par with that of fresh juice in terms of color and turbidity (Rao et al., 2014), color, flavor, and appearance (Xu et al., 2015), color and aroma (Mastello et al. 2018), and taste, appearance, texture, and overall impression (Inada et al., 2018). Three studies showed the acceptance score of HP-treated juice was higher than that of TP-juice, e.g., in color, aroma, and sweetness of sugarcane juice (Huang et al. 2015), in acidity, aroma, and sweetness of white grape juice (Chang et al., 2017), as well as in mouthfeel and overall acceptability of yellow sweet pepper and orange juice blend (Xu et al., 2015). Moreover, Rao et al. (2014) found that acceptability of peach juice aroma was higher in HP-treated peach juice than in both TP- and untreated juice. The authors further reported that TP-juice displayed the lowest rating in color, aroma, and overall impression. However, some cases showed an opposite trend, i.e., reduced acceptability following HPP. For instance, Inada et al. (2018) found a 10% reduction in aroma score of HP-treated jabuticaba juice to untreated juice. Mastello et al. (2018) reported that although HPP showed a similar effect on the volatile profile of Pêra-Rio orange juice as TP, overall acceptability was lower for HP-juice compared with both untreated and TP-juice.

4.2. Effect of HP processing parameters and storage conditions on sensory quality

4.2.1. Pressure and temperature

In order to evaluate the sensory changes as a function of increasing pressure level, the findings reported in the literature and discussion are divided into three intervals: 200–399, 400–600, and 601–900 MPa. Fig. 2 shows a visual overview of sensory changes of juices treated at different pressure, where a higher pressure resulted in decreased perceived intensity of sensory attributes (i.e., flavor loss).

200 to 399 MPa: three studies reported sensory changes to HP-treated products in this pressure range. The intensity of rosin smell in mango juice weakened as pressure increased from 200 to 400 MPa (Zhang et al., 2019). As for acceptability, HP-treated sugarcane juice showed a decrease in the score of color, aroma, and sweetness as pressure increased from 200 to 400 MPa (Huang et al., 2015).

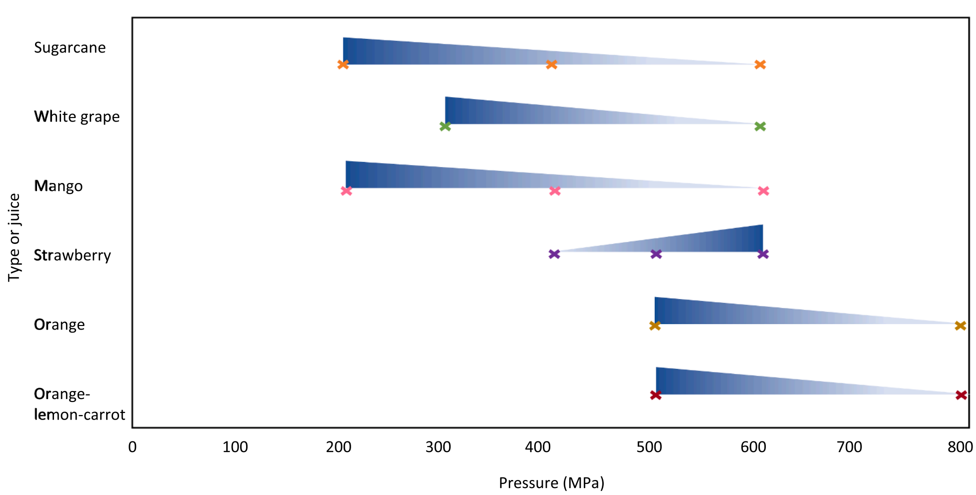
400 to 600 MPa: this pressure range is more often reported in previous studies (Table 3), and a tendency is that juices or smoothies pressured at 600 MPa are different from other pressurized samples. For example, Hurtado et al. (2015) pointed out that HP-smoothies at 600 MPa were clearly different from those at 350 and 450 MPa and were rejected due to flavor alterations. In the study of strawberry juices from Aaby et al. (2018), concurring scores for HP-juices (pressurized at 400, 500, and 600 MPa) were seen for most attributes, except for HP-juices at 600 MPa which had a higher viscosity than other HP-treated samples. Similarly, the intensity of rosin smell in mango juice (at 600 MPa) was higher than that at 400 MPa (Zhang et al., 2019). However, in the pressure range (400–500 MPa), an increased pressure did not cause a significant aromatic difference in cantaloupe juice (Ma et al., 2010). In terms of acceptability, HP-juices pressurized at 600 MPa showed a slight decrease in acidity, aroma, and sweetness of white grape juice than that at 300 MPa (Chang et al., 2017) and in color, aroma, and sweetness of sugarcane juice than that at 400 MPa (Huang et al., 2015).

601 to 900 MPa: Very few studies have investigated the effect of HP-treatment in this pressure range, possibly because pilot studies suggest that alterations to the sensory quality were too large to be acceptable (e.g., Porretta et al., 1995). In addition, such high pressure levels are not relevant in an industrial setting. Fernández García et al. (2001) found that HP-orange juice at 800 MPa showed a significant difference in odor and taste from that at 500 MPa: the former had greater defects whilst the latter was closer to untreated juice. The authors further reported that HP-treated orange-lemon-carrot juice samples at 800 MPa showed a slight but significant odor and flavor defects (more intense carrot aroma, metallic-bitter, and less harmonious) compared to those treated at 500 MPa which, again, were close to untreated ones.

Lastly, the effect of temperature on sensory quality is considered. In most reviewed studies (21 out of 31), HP-treatment was conducted at ambient temperature (20–25 °C). The possibility to set temperature in the pressure vessel depends on the type of HP equipment. Some laboratory scale HP machines can be adjusted to a specific starting temperature, while others operate at ambient temperature (typically around 25 °C). For instance, Ferrari et al. (2010) showed that the lower the processing temperature, the more negligible the overall color variation of pomegranate juice is. The same study further investigated at a pressure of 400 MPa for 5 min and found that juices processed at different temperatures in the range 25–50 °C could be aromatically discriminated by an electronic nose, suggesting that, overall, temperature independently influence sensory quality for HP-juices. In the reviewed literature, only one study considered the different temperatures of the pressure vessel and investigated the effect of HPP temperature on acceptance of the final product (Castellari et al., 2000). The result showed that setting the initial temperature at 50 °C did not improve the preference for aroma and taste of grape juice, compared with that at 20 °C. This result may need further validation, given that the hedonic test was conducted with trained assessors in that paper.

4.2.2. Storage conditions

The quality of fruit juices and smoothies could change during storage due to coexisting chemical (e.g., oxidation) and biochemical reactions if endogenous enzymes or microorganisms are not fully inactivated (Salomão, 2018). Primary storage conditions include temperature and time. As shown in Table 3, only two studies considered room temperature, e.g., Laboissière et al. (2007) and Castellari et al. (2000), whereas cold storage was used in most reported studies (24 out of 31). Hence, the effect of storage temperature (cold vs. ambient) on sensory quality of HP-treated juices and smoothies cannot be evaluated on the basis of the



Type of juice	Sugarcane	White grape	Mango	Strawberry	Orange	Orange lemon-carrot
Sensory profile	Acceptance of color, aroma, sweetness	Acceptance of acidity, aroma and sweetness	Intensity of rosin smell	Intensity of viscosity	Intensity of odor and taste	Intensity of odor and flavor
Reference	Huang et al. (2015)	Chang, Wu et al. (2017)	Zhang et al. (2019)	Aaby et al. (2018)	Fernández García et al. (2001)	Fernández García et al. (2001)

Fig. 2. Intensities of sensory profile changes of HP-juices associated with different pressure levels. Each “x”-mark represents the sensory score (either acceptance score or intensity score) of HP-juice processed at a certain pressure. Intensity bars are graphic ‘interpolation’ between the lowest and highest scores (thinner bars/lighter color indicates lower scores) to provide a visual overview of the directions of the changes.

existing literature. The reminder of this section will therefore discuss results obtained under cold storage conditions.

On the other hand, many studies considered sensory changes occurring as a function of storage time. In total, 20 studies considered sensory changes during cold storage (12 to 120 days). For ease of exposition, changes of sensory quality during storage will be discussed in separate phases: Phase I (<30 days, considered in 9 studies), Phase II (30–100 days, 8 studies), and Phase III (>100 days, 3 studies).

Phase I (<30 days):

Appearance: three studies focused on smoothies have reported color changes in the first 30 days. A general decrease of HP-smoothie color intensity has been evidenced and, conversely, an increase of rust-brown over 21 days storage (Picouet et al., 2016). As for pink color and fresh color, the score for untreated and HP-smoothies (at 600 MPa) decreased significantly between 0 and 30 days of storage (Keenan et al. 2012). Picouet et al. (2016) pointed out that although the color of HP-smoothies deteriorated throughout storage, it was still more similar to untreated ones than TP-smoothies even after 21 days. Besides color, another appearance attribute, turbidity, was investigated in the studies by Keenan et al. (2012) and Hurtado et al. (2017): the former found no significant difference between any fresh or processed (TP and HP) smoothies over 30 days storage, while the latter study found turbidity scores were lower in HP-smoothie than in TP-smoothie after 21 days of storage.

Aroma and taste: aroma and taste changes were considered in five studies, and generally occurred around 20 days of storage compared to untreated one, although the results vary quite substantially depending on the type of juices or smoothies. For instance, Fernández García et al. (2001) observed that changes in odor and flavor of HP-treated orange-lemon-carrot juices were barely noticeable after storage (21 days). Conversely, the sweet taste and overall sensory quality of HP-smoothies decreased throughout the 21 days of storage (Picouet et al. 2016). This is consistent with the study of Hurtado et al. (2017) that the loss of overall sensory quality of HP-smoothies began to be relevant at 21 days of chill storage (4 °C). However, in the study of Keenan et al. (2012), no significant changes were observed for all untreated or treated (HP and TP) samples in most flavor attributes within 30 days, e.g., apple aroma and flavor, orange aroma, banana aroma, and flavor, acid aroma and flavor, overall flavor. The same study reported that the effect of HPP (600 MPa) on fresh aroma and fresh flavor was not consistent as a significant reduction occurred between 0 and 15 days, but then the intensity of these attributes increased between 15 and 30 days (this inconsistence was not explicitly discussed by the authors but could be the result of variable enzyme activity within fresh samples before processing). Moreover, when HP and TP-treated samples were compared, HP-watermelon juice showed a significant difference on the 1st and 12th day (Aganovic et al., 2016), possibly due to the activity of peroxidase and polyphenol oxidase enzymes (Zabetakis et al., 2000). Picouet et al. (2016) and Hurtado et al. (2017) had the same conclusion: the intensity of overall sensory quality of HP-smoothie was higher than that of TP-smoothie for 21 days, but the intensity of off-flavor was lower in HP-smoothie than in TP-smoothie for 28 days. The off-flavor could be explained by a result of thermal degradation of flavoring compounds during fruit heating (Ludikhuyze et al., 2003). Yet, with respect to the intensity of overall odor and flavor, scores from HP- and TP-smoothies were similar in the study of Hurtado et al. (2017), although overall flavor decreased in the HP-smoothie as from day 21. These authors also found that HP-smoothies were more acidic than TP-treated samples after 14 days.

Mouthfeel: mouthfeel attributes were considered in three studies related to storage time. Hurtado et al. (2017) showed HP-smoothie presented lower scores of sliminess than TP-smoothie on the 14th and 21st day but not on the 28th day, whereas grittiness scored similarly in both types of smoothies over time. This is consistent with the study of Picouet et al. (2016) that the intensity of sliminess in HP-smoothie was lower than in TP-smoothies. By contrast, graininess and separation showed no significant changes for any fresh or processed (HP and TP) smoothies over 30 days of storage (Keenan et al. 2012).

Acceptability: acceptability during storage time was investigated in three studies. Untreated and HP-treated litchi juice showed no significant difference in terms of odor, acidity, sweetness, and overall acceptability after 4 weeks of storage (Zheng et al., 2014). Martins et al. (2022) also found that consumers perceived HP-treated mixed juices closer to untreated juices than TP-juices during the 28 days of storage. By contrast, a significant difference for acceptability was observed only between the 1st and 30th days: most of the smoothie samples were deemed acceptable, except for fresh samples on day 30, which were unacceptable (Keenan et al., 2011). This could be attributed to a buildup of oxidative or enzymatic byproducts and an increased microbiological load, which could lead to off-flavors developing within the non-processed controls.

Phase II (30–100 days):

Appearance: two out of eight studies described appearance change and showed a similar trend: there were no significant changes in color between untreated and processed (HP and TP) orange juices within 12 weeks (84 days) (Baxter et al., 2005) or between HP-treated strawberry juice over 35 days (Aaby et al. 2018). This can be explained by HPP having a minor impact on color associated compounds such as carotenoids, anthocyanins, and polyphenols (Koutchma et al., 2016).

Aroma and taste: aroma and taste changes were found in three studies and reported different effect over the storage period. In a relatively short time (35 days), concurring scores of flavors were observed for the most processed (TP and HP) strawberry juices (Aaby et al., 2018). When storing for 60 days, HP-treated white grape juice displayed stable sweetness and acidity levels and presented less grass aroma, off-flavor, and cooked fruit aroma, but a slight decrease in fresh fruit aroma was noted (Daoudi et al., 2002). After 12 weeks (84 days) of storage, according to Baxter et al. (2005), all orange juice samples (untreated, HP and TP) followed a general trend: a decrease in sweet odor and sweet flavor, overall strength of the orange odor, and overall strength of orange flavor, sourness taste and aftertaste, and duration of aftertaste, alongside an increase in aged odor, artificial odor, fermented odor, and processed flavor. Furthermore, the authors found that the processed juices (HP and TP) were lacking in fresh juice aroma and taste characteristics by 8–12 weeks (56–84 days).

Mouthfeel: only one paper (Aaby et al., 2018) investigated mouthfeel in this time range and reported that after 35 days of storage, the degree of viscosity between untreated, TP- and two HP-treated strawberry juice were similar.

Acceptability: six out of eight studies discussed acceptability changes following storage, evidencing a clear general trend: HP-treated samples were liked more or at least similarly compared to both untreated and TP-treated samples. For instance, HP-treated orange juice was judged of superior sensory quality as compared to a similar TP-treated juice, retaining more flavor of fresh juice, for up to 100 days of storage (Polydera et al., 2003, 2005). Besides, HP-treated apple juice preserved its general perception for 34 days (Juarez-Enriquez et al., 2015). After 42 days, minor differences with respect to appearance were observed for untreated and processed (TP and HP) pomegranate juice, but general acceptability did not change (Rios-Corripio et al., 2020). Nayak et al. (2017) also reported that HP- and TP-treated elephant apple juice was acceptable in odor and taste up to 50 days. However, consumer perception for HP-treated products could change along with storage condition. In the study of Baxter et al. (2005), consumer acceptance of HP-orange juices changed over time: 1) the HP-treated sample stored at 10 °C was disliked slightly, but that stored at 4 °C was still acceptable after 1 week; 2) no significant differences between HP-treated samples (stored at 4 and 10 °C) were found after 2 weeks; 3) all HP-treated samples were "neither liked nor disliked" by consumers after 4 weeks; 4) the HP-treated sample stored at 10 °C was not liked by consumers but that stored at 4 °C were "neither liked nor disliked" after 8 weeks; 5) after 12 weeks, the HP-treated sample stored at 4 °C was "liked slightly" but that stored at 10 °C was “disliked slightly”.

Phase III (>100 days):

Aroma and taste: only one study from Parish (1998) considered the effect of storage (16 weeks, 112 days) on the sensory attribute of orange juice. The results showed scores of HP-juices at week 16 were substantially higher than that at 4 or 8 weeks, indicating large flavor differences from fresh juices, however, during the storage, HP-juices generally maintained their flavor advantage over TP-juices.

Acceptability: there were only two studies investigating acceptability beyond 100 storage days. In the study of Bansal et al. (2018) regarding whey-based sweet lime juice, HP-treated sample had an acceptable flavor and color, resulting in the highest overall acceptability score within the progression of storage (120 days). An opposite trend was found in the study of Hulle and Rao (2016) about aloe vera-litchi mixed beverages. The changes in color, aroma, taste and phase separation were very noticeable after 80 days of storage, possibly due to residual enzyme activity, and after 100 days, HP-treated sample showed pronounced browning, which was disliked by the panelists, and both HP- and TP-juice reached an unacceptable level of taste, aroma and pronounced phase separation.

Based on the above reviewed results, a proposed visual summary of the main trends of sensory changes associated with storage time is given in Fig. 3. It shows 1) at the beginning of storage, untreated and HP-treated samples could be expected to have comparable sensory quality and acceptability, whereas TP-treated samples showed changes and losses in sensory attributes compared to both (Daoudi et al., 2002; Huang et al., 2015; Zheng et al., 2014; Polydera et al., 2005; Bansal, Jabeen, Rao, Prasad, & Yadav, 2018; Hurtado et al., 2017; Nayak, Rayaguru, & Radha Krishnan, 2017; Picouet et al., 2016; Swami Hulle & Srinivasa Rao, 2016), 2), as storage time increases, a decrease in the intensity of most sensory attributes was observed (Fig. 3a)(Keenan et al., 2012; Hurtado et al., 2017; Picouet et al., 2016; Fernández García et al., 2001; Daoudi et al., 2002), though the level is still higher than TP-product and 3) as storage time increased, a decline in acceptability of untreated and treated juice/smoothies occured (Fig. 3b) (Keenan et al., 2011; Bansal, Jabeen, Rao, Prasad, & Yadav, 2018; Baxter, Easton, Schneebeli, & Whitfield, 2005; Swami Hulle & Srinivasa Rao, 2016). Importantly, the general trend is that the degradation of HP-products does not occur as fast as untreated products.

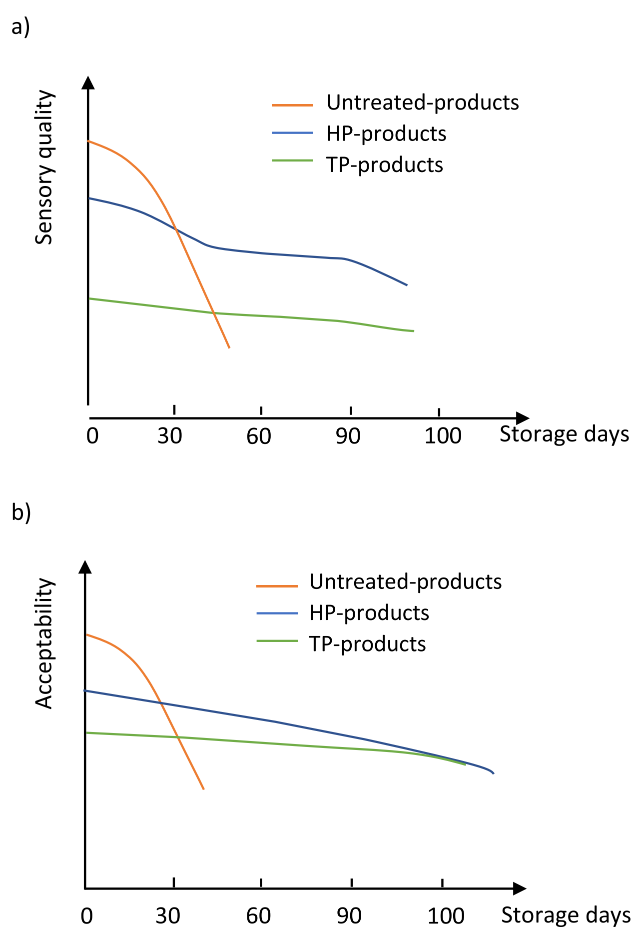


Fig. 3. The proposed changes of sensory quality (a) and acceptability (b) during storage, based on summaries in reviewed papers.

5. Discussion and directions for future research

This paper reviewed research studies focusing on the sensory profile of HP-treated fruit juices and smoothies and elaborated on three main aspects: sensory evaluation methods, the general sensory quality of HP-treated products, and the effect of processing conditions (HPP parameters and storage conditions) on the sensory profile of the final products. Most reported studies found that sensory profiles of HP-treated juices and smoothies were closer to fresh samples than to samples treated by TP. However, the literature also evidenced a significant degree of heterogeneity in the findings suggesting that fruit juices and smoothies are complex systems and that the impact of HPP on sensory characteristics depends on the material (formulation of juice/smoothie) and specific process parameters.

To obtain valid sensory information, methods and assessors should be carefully considered. Generally, trained and untrained assessors should be used for analytic and affective methods, respectively. However, a pervasive mismatch between methods and panelists was observed in the literature on HP-treated juices and smoothies, which reduces the accuracy and validity of sensory results: a mainstream consumer may or may not be able to evaluate specific sensory attributes in a descriptive task (and their interpretation would be ambiguous anyway); vice versa, hedonic ratings obtained from a small group of experts or trained panelist do not reliably reflect what average consumers might want or like in a product. This issue was primarily encountered for hedonic tests, in which most studies used trained assessors or product experts to evaluate the degree of (consumer) acceptability of the test products. Also problematic is the use of small sample sizes, as all studies but one fall below current recommendations of employing at least 50–100 consumers (Mammasse and Schlich, 2014). Collectively, these problems warrant further research to document and validate the sensory quality and, especially, the consumer acceptability of these products.

Most studies reported minor changes in sensory profile between HP- and untreated juices/smoothies after processing, while thermally processing caused a larger loss of sensory quality (e.g., Baxter et al., 2005; Daoudi et al., 2002; Hurtado et al., 2017). The reason that HP-treated products remain stable in terms of sensory quality is mainly due to the HP-induced inactivation of several oxidative and pectic enzymes (Chakraborty et al., 2014) and low effect on the structure of small molecular flavor compounds (Oey et al., 2008). Besides, one can expect that overall acceptance for HP-treated products should be closer to that of fresh ones due to small sensory changes after processing, and indeed most papers presenting hedonic data support this conclusion (though one should be careful to take the results at face value due to the issues outlined earlier).

Fruit juices would normally need to be processed at ≥ 400 MPa for a few minutes at ≤ 20 °C to significantly reduce the number of yeasts and molds (Patterson 2005). However, the literature reports a large range of different combinations of pressure and temperature (Table 3), leading to either desired or undesired changes in sensory quality. An example of the former, Rao et al. (2014) indicated HP-treated peach juice had greater typical fresh peach aromas than TP- and untreated juice, as the content of the characteristic aroma components of peach juice, such as gamma-caprolactone and gamma-decalactone, increased dramatically after processing (in that study: 600 MPa for 10 min at room temperature). The most extreme example of HPP resulting in undesired changes was in the study by Porretta et al. (1995) that tomato juices became inedible due to a strong rancid taste after processing (500 MPa for 3 min, 700 MPa for 6 min, and 900 MPa for 9 min). Another evident finding from reported studies (Table 3) is the sensory quality of final products differed to a high extent along with different storage conditions. As emphasized earlier, cold storage (≈4 °C) was most commonly employed (Table 3) as it is effective in extending the shelf life (Polydera et al. 2003), and in preserving sensory profile (e.g., Baxter et., 20015). Hence, the combination of HPP parameters and storage conditions is important when giving a comprehensive insight into the impact of HPP on fruit products.

As for consumer perception, although several aspects (e.g., price, package, familiarity) affect the commercial feasibility of HP-treated juices and smoothies, sensory properties are likely to be the main driver of consumer adoption. However, how specific sensory properties of HP-treated fruit products drive consumer perception has not been thoroughly studied yet in the available literature. Against this backdrop, it is advisable in future studies to combine analytic and hedonic tests of HP-treated products, rather than either of them in isolation. Only one out of the reviewed studies (Baxter et al., 2005) presented both sensory and consumer preference data collected on the same orange juice samples. The authors showed that 79% of the variation between sensory characteristics of orange juices could explain 82% of the variation in consumer preferences. Furthermore, they highlighted which flavor attributes (e.g., sweetness, orange flavor) correlated with overall liking, and which were negatively correlated with it (e.g, fermented and artificial odor). This study pointed out intrinsic relations between sensory characteristics and consumer perception of fruit products. Similar approaches should be considered in future studies to define important sensory determinants of acceptability, as well as to examine the contribution of each sensory attribute to consumer preference. One way to achieve this is using multivariate data analysis methods, such as preference mapping, to identify sensory attributes negatively or positively associated with consumer preference (Giacalone, 2018). Looking at the relationships between sensory quality and consumer perception would enable a better understanding of drivers of liking in HP-treated fruit juices and smoothies, and, if combined with instrumental data and carefully designed experiment, would help in selecting the most suitable processing conditions to maximize consumer preferences.

6. Conclusions

Over the last 25 years, HPP has been successfully applied to fruit juices and smoothies to enhance the safety and shelf-life of these products while reducing the negative effects of thermal processing on sensory and nutritional qualities. Most studies reviewed in this paper indicate that the sensory profiles of HP-treated juices and smoothies were closer to untreated samples than to TP-ones, confirming that HPP can maintain the most desired sensory attributes of untreated juice over TP. Fresh- and natural-like attributes of HP-treated juices/smoothies could therefore properly fit consumer demand as these attributes are valued by consumers today. Accordingly, the consumer acceptability of HP-treated groups was also reportedly closer to untreated samples than the TP-ones. Yet, results were not always consistent among the reviewed papers, suggesting that the sensory quality of HP-treated fruit products is product- and process dependent and that additional research on the effect of HPP on sensory profiles is advised. Some methodological issues with the sensory studies emerged, particularly concerning hedonic testing of HP-treated juices and smoothies, which generally employed very small and unrepresentative panels, indicating a clear need for further research to validly document especially the consumer acceptability of these products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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