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Abstract

This work aims to compare the impact of three thermal (helical coil heat exchanger HCHE, ohmic heating OH, and mild pasteurization MP) and one non-thermal (high-pressure processing HPP) treatments on orange juice by using industrial plants. Nutritional (total phenolic content (TPC), ascorbic acid (AA) and total antioxidant capacity (TAC)), physical (viscosity, colour, browning index (BI) and suspended pulp (SP)), sensory (Triangle test and QDA) as well as chemical (^{1}H NMR spectroscopy) aspects were analysed. Results revealed a significant (p<0.05) increase in viscosity for HPP (+ 20%) compared to untreated samples while the opposite effect was observed for all thermal treatments (-22%). The lowest a* values were observed in HPP and HCHE samples. Total phenolic content decreased significantly only in HCHE (-14%), while the highest ascorbic acid content was observed in HPP samples and it resulted not significantly different from untreated. Regarding the chemical profile, treated samples (except for MP) led to a significant (p<0.05) decrease of all selected marker peaks, mainly including sugars (alpha- and beta-glucose, beta-fructose, and sucrose) and amino acids compared to untreated ones. HPP samples showed a similar sensory profile if compared with the untreated sample, showing only a significant difference (p<0.05) in terms of orange aroma; on the contrary, OH, HCHE, MP rated the lowest acceptances due to, among all considered descriptors, orange aroma, cooked aroma, sweetness, cooked taste.

Keywords: Thermal processing; colour; phenols; viscosity; sensory evaluation

Introduction

The global consumption of fruit-based beverages reached 95.7 billion litres in 2018 of which soft drinks accounted for 37.2 billion. This was followed by nectars (10.9 billion), 100% juice (16.6 billion), and powdered and concentrated juices (30.4 billion). Citrus juices including orange juice (OJ), made from the endocarp of the *Citrus sinensis* fruit, accounts for 60% of all juices and juice-based beverages in Western Europe (AIJN, 2014). Orange juice represented 43.8% of the juice market, as well as in the juice drinks segment, with 26.2% of the market (Neves et al., 2020). Orange juice is an essential source of bioactive and antioxidant compounds such as vitamin C (Davey et al., 2000), carotenoids (Rodriguez-Amaya et al., 1997), provitamin A and flavanones (Gil-lzquierdo et al., 2001). In the last decades, the demand for more natural, functional, quality, and minimally processed foods has increased exponentially (Bansal et al., 2015).

While pre-pasteurized and minimal processed orange juices have favourable sensory and nutritional characteristics, they are synonymous with having a short shelf life due to the presence of spoilage causing bacteria, yeasts, and endogenous enzymes (Lee & Coates, 1999).

Thermal pasteurization (TP) is often used to inactivate bacteria and endogenous enzymes and therefore extend the shelf life of OJ. However, TP may cause irreversible sensorial, nutritional, and physical-chemical changes in the OJ (Braddock, 1999). For example, OJ has been shown to lose representative aroma and taste components, and vitamin C during thermal treatments (94°C/30s) and subsequent storage (4°C/15 days) (Yeom et al., 2000). Moreover, regarding the energy consumption of the process, Pardo and Zufía (2012) studied the environmental impacts of traditional and novel preservation technologies through LCA methodology: Authors reported that thermal technologies showed a high environmental load, related directly or indirectly to the fossil fuel combustion processes involved in the thermal energy generation

phase. Improving the heat exchange efficiency through design optimization using e.g., Computational Fluid Dynamics (CFD) techniques (Rinaldi et al., 2019) could be a valuable way to reduce energy consumption in traditional thermal processes. Among heat exchangers **available to date, helical coil heat exchangers are widely used in industrial applications due to the compact structure, high heat transfer coefficient, and therefore represent a promising choice for energy saving in the food industry (Jayakumar et al., 2008; Jayakumar et al., 2010).** Many researchers have identified that a complex flow pattern exists inside a helical pipe due to which the enhancement in heat transfer is obtained thanks to the development of secondary flow. The curvature of the coil governs the centrifugal force while the pitch (or helix angle) influences the torsion to which the fluid is subjected.

High-pressure processing (HPP) has received a lot of attention in the last years because of the widespread implementation of the clean-label approach and its minimal impact on sensory and nutritional qualities (Roobab et al., 2021). HPP has been demonstrated to be effective in reducing microbial flora in fruit beverages while retaining the sensory quality of the **product without affecting** the structure of small molecules such as bioactive substances (**Bull et al., 2004; Rastogi et al., 2007; Oey et al., 2008; Barba et al., 2010**). This process applies high hydrostatic pressure to inactivate several enzymes and pathogenic bacteria that cause food product quality degradation: in particular, sufficiently high pressures and long processing times (700 MPa/1 min) in HPP treatments of OJ were more effective at preserving the turbidity of OJ, that can be lost during storage **because of enzymatic** de-esterification and degradation by pectin-esterase (Goodner et al., 1999). Electrical resistance heating, joule heating, and electro-heating are all terms **applied t**: ohmic heating (OH). **OH, may be a favourable food processing technology because it provides rapid and uniform heating resulting in reduced thermal damage to the product and fouling phenomena in the heating section when compared to traditional thermal pasteurisation. Few studies have evaluated** the application of this technology to process orange juice and compared simultaneously with other treatments (Leizerson and Shimoni, 2005a and 2005b; **Tumpanuvatr and Jittanit 2012; Demirdöven and Baysal, 2014; Hashemi et al.,2019**).

By considering the quality parameters of OJ, several thermal and non-thermal technologies have been tested and evaluated to process and stabilize OJ, such as conventional thermal methods, atmospheric cold plasma, ozone treatments, microwave-assisted pasteurization, HPP, pulsed electric field, OH (Goodner et al., 1999; Ayhan et al., 2002; Gil-lzquierdo et al., 2002; Sanchez-Moreno et al., 2005; Leizerson et al., 2005ab; Baxter et al., 2005; Patil et al., 2009; Velazquez-Estrada et al., 2013; Alves Filho et al., 2016; Brugos et al., 2018; Atuonwu et al., 2020).

Atuonwu et al. (2020) studied microwave, OH, HPP, and conventional thermal methods for energy consumption per litre of orange juice, as well as associated greenhouse gas emissions. **Despite innovative technologies (especially OH) showing significantly higher efficiency, the high costs of grid electricity results in poorer processing economics when compared to conventional gas-fired technologies. However, the authors stated that with shifting trend towards renewable sources of energy, the ohmic technologies will eventually become more economically feasible**. **Atuonwu et al. (2020) did not observe significant** differences among the different thermal and non-thermal methods for some specific OJ quality parameters (flavour compounds, vitamin C), **this may be due to the application** of mild thermal treatment conditions and short processing times employed. Baxter et al., (2005), despite demonstrating that the HPP (600MPa / the 60s)-treated orange juice was acceptable for odour and flavour profile up to 12 weeks of storage at 4°C, did not report significant differences related to the sensory profile and shelf life compared to thermally pasteurized OJ. **Conversely, other studies reported superior product quality characteristics for OJ processed using non-thermal technologies: particularly preservation of bioactive and thermolabile compounds were reported to be favourable in HPP than in pasteurization (Cortés et al., 2008; Vieira et al., 2018).** other researchers reported that also OH was more gentle than standard pasteurization in retaining some specific flavour compounds (Leizerson and Shimoni, 2005a and 2005b).

Understanding the effects of various technologies on juice quality features is critical for designing and optimizing technological parameters to generate high-quality foods. Thus, the present work aims to investigate the effects of mild pasteurization, and helical coil heat exchangers compared to ohmic and high-pressure processing for the pasteurization treatment of orange juice. In particular, colour, viscosity, total phenol content, ascorbic acid content, and sensorial quality were investigated.

Materials and Methods

Samples, preparation, and storage

Fresh orange juice (untreated UNT) was prepared from *Citrus sinensis.* A mix of Valencia and Navel varieties were purchased from MACE S.R.L (Ferrara, Italy). The OJ was subjected to different treatments: mild pasteurization (MP), a helical coil heat exchanger (HCHE), ohmic heating (OH) and high hydrostatic pressure (HPP). Thermal pasteurization represents the **widest** treatments for obtaining a shelf-stable product while HPP was tested as the less impacting treatment for a refrigerated product. All the samples were stored at a refrigerated temperature (+4 ± 1°C) until the analyses were performed.

1. Mild pasteurization (MP)

Mild pasteurization treatments were carried **out in a** pilot plant at the University of Parma laboratories as reported in Rinaldi et al. (2018). The treatment was performed at a flow rate of 20 L/h and a residence time of 20 s at 72 ± 1°C as **reported by** Vervoort et al. (2011) with a pasteurizing effect after $F_{90}^{6.7} = 7 * 10^{-4}$. After the **MP** treatment, OJ was rapidly cooled using a continuous cooling section to a final temperature 20 ± 1°C, then packed in PET bottles under aseptic condition and stored at refrigerated temperature (+4 °C) for further analysis. **Treatment was repeated three times and 5 litres of OJ were treated each time.**

2. Helical coil heat exchanger (HCHE)

A helical coil heat exchanger (HCHE) (Sterideal® HX Coil, John Bean Technologies, Chicago, Illinois, United States) **was studied which consisted of** a helical coil stainless steel 304 tube with an internal diameter of 30 mm and a total length of 8.5 m. During the treatment, the flow rate was set to 2000 L/h, fastest particle holding time of 7.72 s at 97 °C. Thermal treatment was designed with a pasteurizing effect equal to $F_{90}^{6.7} = 1.5$ for as su**ggested by Leizerson & Shimoni (2005a) by achieving a complete reduction of relevant pathogens and spoilage bacteria as well as a residual activity of thermostable PME of about 5% (Velázquez-Estrada et al., 2012).** During tests, temperatures at the beginning and the end of the holding section were measured using a resistance temperature detector Pt100 with a diameter of 3 mm (Endress+Hauser AG Reinach BL, Switzerland). **Recorded temperature profile during tests confirmed the target F-value with a value equal to $\boldsymbol{F_{90}^{6.7} = 1.54}$.** After thermal treatment, the samples were rapidly cooled in the aseptic portion of the plant, for about 5 min to reach 25 °C and aseptically packed in 10 L bags (Goglio Spa, Milano, Italia - PE/MET/PE, thickness 77 µm using of commercial plant (AF200 Classic Aseptic Filler, John Bean Technologies, Chicago, Illinois, United States). **Trials were performed on an industrial plant in duplicate and for each trial approximately 400 kg of the product was used.**

3. High-pressureure processing (HPP)

High hydrostatic pressure treatments were conducted in a 300 L high-pressure plant (Avure Technologies Inc., Erlanger, Kentucky, United States). Samples were packed in PET bottles with an internal volume of 250 ml. An indirect direct method for generation of high isostatic using means of cold water (4 °C) was used, and the temperature increase due to compression was not higher than 2-3 °C/100 MPa. **HPP** treatments were conducted at 550 MPa for 90 s, chosen based on the goal of inactivation of pectin methyl esterase (PME) (Nienaber & Shellhammer, 2001) and to be **microbiologically safe (Linton et al., 1999).** The treated samples were then stored at a refrigerated temperature (+4 °C). **HPP treatments were conducted in triplicate and for each repetition 15 bottles were treated.**

4. Ohmic heating (OH)

Ohmic heating (OHM, Sterideal DT ®, John Bean Technologies, Chicago, Illinois, United States): temperature increases up to 97 ° C was obtained using an ohmic heater at a flow rate of 2,000 L/h obtaining the same sterilizing effect reported above for HCHE. The industrial plant used the same holding section already described for HCHE and experimental F-value was equal to $F_{90}^{6.7} = 1.60$. **The electrical power required was precalculated using plant software at the set temperature based on samples electrical conductivity measured by using a digital conductivity meter (0.413 Sm^{-1} at 25 °C and 0.832 Sm^{-1} at 60 °C) and by reported values (Leizerson & Shimoni, 2005a). The final precise electrical power adjustment was then obtained using a feedback control on product temperature measured at the outlet of the ohmic section and the product used for this setting was discarded**. After thermal treatment, the samples were cooled and aseptically packed in 10 L bags (Goglio Spa, Milano, Italia - PE/MET/PE, thickness 77 μm). **Trials were performed on an industrial plant in duplicate and for each trial, approximately 400 kg of the product was used.**

The degree of thermal damage in thermal treatments was expressed in terms of cook value C_{Tref}^{z} and obtained from the integration of the heat penetration curve:

$$C_{Tref}^{z} = \int_0^t 10^{(T - T_{ref})/z} \, dt$$

where:

t = **time at T**

T = temperature of the product at different times

T_{ref} = reference temperature; set equal to 100 °C

z = temperature increase that induces a 10-fold increase of the reaction rate of the chemical reaction taken as a reference; z was set at 33°C.

Physical and chemical characterization of orange juice

Total soluble solids, suspended pulp, and pH

The total soluble solids of orange juice (°Brix) were determined in triplicate at 25°C by refractometer (Model 2WAJ, Optika, Italy). The pH was measured in triplicate using a pH meter (Model 3150, Jenway, UK). Suspended pulp was measured using **the** IFU Method No 60 (**2005**).

Viscosity

The apparent viscosity profile of the orange juice samples was measured with concentric cylinder geometry (Couette cell) mounted on Ares strain-controlled (ARES) rheometer (TA Instruments, New Castle, DE, USA) and connected to a thermostatic bath (NESLAB RTE 111, Thermo Fisher Scientific, Massachusetts, USA) for temperature control during the analysis. The dimensions of the geometry were 34 mm cup diameter, 32 mm bob diameter, and height of 33 mm. 15 mL of the sample were transferred using a graduated cylinder to the rheometer cup set at 25°C and sample temperature left to equilibrate for 2 min before starting the test. The tests were performed from 10 to 200 s-1 shear rates and viscosity values at 100 s-1 were compared.

Colourimetric analyses

The colour of orange juice samples was measured busing image analysis with a desktop flatbed scanner (Hewlett Packard Scanjet 8200, Palo Alto, CA, USA) at 600 dpi of resolution, equipped with **a cold cathode lamp for reflective scanning. During image acquisition, the scanner was held in a black box, it excludes surrounding light and external reflections. Flatbed scanner colour (RGB) was corrected as previously reported by N'Dri et al. (2010) and converted to CIE Lab using of ImageJ software (National Institutes of Health (NIH), Maryland, USA).** The colorimetric analysis was performed in triplicate.

The browning index (BI) was measured using the method of Tiwari et al. (2008) and absorbance was obtained at 420 nm by using a Phillips PV 8700 spectrophotometer.

Total phenolic content (TPC) and ascorbic acid content

The Folin-Ciocalteu colorimetric test (Papagiannopoulos et al., 2004) was used to calculate the total phenolic content (TPC) of the samples. 1 mL of sample was mixed vigorously with 70 mL pure water and 5 mL Folin-phenol Ciocalteu's reagent (Sigma-Aldrich, Switzerland). After 5 minutes, 10 mL of a saturated sodium carbonate solution was added, and the sample was brought up to a final volume of 100 mL with distilled water. A UV–V is spectrophotometer was used to assess absorbance after 60 minutes at 720 nm. Total phenols were calculated as mg of (+)-catechin equivalents per kilogram of total phenols. Samples were homogenized and diluted with distilled water before being used in a colorimetric experiment.

HPLC–DAD was used to determine the amount of ascorbic acid in the sample. Before HPLC analysis, materials were diluted with a 6 percent aqueous metaphosphoric acid solution, uniformly mixed with Ultra-Turrax (T25 basic IKA®, IKA-Werke, Staufen, Germany), and filtered using a paper filter and a 0.45 μm syringe drive filter unit. Solutions of 0.5 to 100 mg/kg of L-ascorbic acid in 6% metaphosphoric acid were made as calibration standards.

Chemical profile analysis

^{1}H NMR spectroscopy method was used for the analysis. For ^{1}H NMR analysis, 300 μL of OJ samples were added to 400 μL of D_2O (Sigma Aldrich, Saint Louis, MO, USA) and 100 μL of 3-(trimethylsilyl)-propionate-d4 sodium salt, 98% atom D (TSP) (Sigma Aldrich, Saint Louis, MO, USA) at 1 mg mL^{-1} as internal standard. After centrifugation (at 4 °C, 3900 g, for 30 min), 600 μL of the supernatant were filtered and transferred into 5 mm NMR glass tubes. For each thermal treatment, triplicates were prepared and analyzed NMR spectra were recorded on a Bruker Avance™ III 400 MHz NMR Spectrometer (Bruker BioSpin, Rheinstetten, Karlsruhe, Germany) operating at a magnetic field-field strength4 T. Spectra were acquired at 298 K, with 32 K complex points, using a 90° pulse length and 3 s of relaxation delay (d1). A total of 128 scans were acquired with a spectral width of 9595.8 Hz and an acquisition time of 1.707 s. The relaxation delay and acquisition time allow the complete relaxation of the protons, allowing their integrals for quantitative purposes.

Acquired ^{1}H NMR spectra were processed applying a Fourier transform, transferred to MestReNova software (release 6.0.2, Mestrelab Research, Spain) and referenced to TSP (0 ppm). The assignment of ^{1}H NMR signals was supported using data available in the literature (Pham et al., 2021) and the metabolomics data repository for NMR Metabolomics (bmrb.io). An integration pattern was defined by choosing buckets manually in the range between 0 and 9 ppm was considered spectra in the overlapped form. This procedure permitted the choice of buckets sufficiently large to compensate for the small chemical shift fluctuations in each spectrum, corresponding to a defined signal or to a group of signals, which simplifies the interpretation of statistical results. The defined pattern was used for automatic integration of all spectra and referred to TSP area.

Sensorial analysis

All sensorial tests were carried out at Stazione Sperimentale per l'Industria delle Conserve Alimentari (SSICA) in a laboratory compliant to UNI EN ISO 8589:2010. **Sensorial test were carried out on all samples except for MP: mild pasteurization is a stabilization technique that is generally coupled with refrigerated storage and no complete inactivation of microorganisms. Based on the microbiological results (data not shown), MP samples were excluded from sensorial analyses for safety reasons.** Initially, a consumer discriminant test was conducted with 23 untrained subjects (13 males, 10 females: average age 25 ± 8 y). The participants were asked to refrain from eating, smoking, drinking, or chewing gums for 1 h prior to testing. A triangle forced-choice procedure was used to determine differences between samples from different treatments. Participants were requested to determine which sample was the odd one. Each sample was identified by a 3-digit code and the order of sample presentation was randomized. Moreover, a quantitative descriptive analysis (QDA) was performed with 10 trained judges on the following attributes: colour orange aroma, cooked aroma, off-flavours, sweetness, bitterness, acidity, cooked taste, off-taste, taints, overall liking. The intensity of each attribute was rated using unstructured line scales (scaled 0–10).

Statistical analysis

SPSS (v. 27.0, SPSS Inc., Chicago, USA) was used to calculate means, standard deviations and to perform one-way analysis of variance (ANOVA) with Tukey HSD post-hoc test to evaluate the significant differences among treatments ($p<0.05$).

Results and discussion

Physico-chemical analyses

The total soluble solids content and pH of the orange juices and ranged from 10.8 to 11.3° Brix and from 3.6 to 3.8, respectively (results not shown), and presented not significant differences between treatments. Our results are in accordance with Demirdoven et al. (2014), **who** did not observe significant differences among OH, pasteurized and raw OJ samples related to water soluble matter and pH values. Also, Timmermans et al., (2011) **reported no** statistical differences in terms of pH and °Brix for OJ untreated and treated with HPP and mild heat pasteurization.

Viscosity

The viscosity data of orange juices at 100 s^{-1} are **shown** in **Figure 1;** among the samples, two different trends were **observed**: HPP samples showed significantly higher viscosity compared to UNT while, all thermally treated OJ expressed significantly lower viscosity. This result agrees with previous studies on OJ treated with HPP (Polydera et al., 2005; Xu et al., 2015). **Generally, larger, and irregular particles are reported to contribute to a higher viscosity in fruit juices due to the higher hindrance to the flow compared to finer and more regular particles (Espinosa-Muñoz et al., 2013). Suspended pulp results (Table 1) partially confirmed this observation with the highest value of SP % in HPP samples among the other treated samples. All thermal treatments (HCHE, OH and MP) despite their very low cook values, probably caused the non-enzymatic degradation and the base-catalysed splitting of pectin chains via the β-elimination reaction with a consequent reduction of viscosity. Suspended pulp results are not significantly different between UNT and HPP (Table 1) but probably, despite the same total weight of sedimented pulp, volume of particles could be different due to gelatinization of pectin caused by high pressure as previously reported (Agcam et al., 2021).** Sanchez-Moreno et al., (2005) observed that HPP and high pasteurization OJ showed significantly lower viscosity than freshly squeezed orange juice.

Colour analysis

Colorimetric parameters *L** and *b** did not present significant differences among the samples (**Figure 2**) while, **about** *a** values, a shift to negative values of this latter parameter (indicating a less red colour) was **observed for** all the treatments **except fo**r HPP. This result agrees with Sánchez-Moreno et al. (2005) that reported the same trend after thermal and HPP treatments. In addition, total colour difference (ΔE) was calculated and the highest value was obtained for MP (3.0) samples while the lowest one for HPP (2.0), as expected (Oey et al., 2008).

On the contrary, no significant differences were observed in hydro-soluble colour at 420 nm (**Table 1**) that is generally used as an indicator of non-enzymatic browning in fruit juices **(Valdramidis et al., 2010). This result was in** adherence with the non-significant differences in colour measured by sensorial analysis (**Table 3**). Finally, HPP allowed the complete retention of suspended pulp compared to UNT as previously reported by Parish (1998), due to the absence of shearing by pumps in the thermal pasteurization systems.

Total phenolic content (TPC), total antioxidant capacity (TAC) and ascorbic acid (AA) content

Total phenolic content (TPC) of untreated samples was 747 mg/L (**Table 1**) and HCHE was the only treatment that caused a significant decrease of this parameter; no significant differences were observed for other treated samples. This result agrees with calculated cook values for thermal treatments: HCHE presented the highest value of C_0 (0.69 min) followed by OH (0.42 min) **due** to the very high heating rate and by MP (0.15 min) thanks to the low treatment temperature. Similar results were obtained for ascorbic acid content and total antioxidant capacity (**Table 1**). Moreover, results agree with sensorial data with reference to bitterness: phenolic compounds are generally recognised as responsible of bitterness in OJ and no differences were observed for this descriptor (**Table** 3)

TPC in OJ measured by Vieira et al., (2018), revealed no significant changes between the HPP and thermally pasteurized samples before storage. However, after storage, TPC decreased in the thermally pasteurized **samples** than in HPP. Sanchez-Moreno et al., (2005) observed that HPP treatment increased the content of naringenin (20.2%), and hesperidin (39.9%) and this change may be due to the modification in the structure of vesicles in the orange juice and to a greater extraction of flavanones and other bioactive compounds such as carotenoids.

HPP samples also showed the highest value in terms of AA **when** compared to the other treated samples, but a similar value **when** compared to UNT (**Table 1**). This observation was also in accordance with previous findings that reported a lower degradation of AA in beverages treated with HPP when compared to thermally treated **samples** (Barba et al., 2010). Also concerning the TAC, UNT together with HPP showed the highest values (23.0 ± 1.15 μmol_{Trolox}/g and 22.4 ± 1.18 μmol_{Trolox}/g, respectively) **when** compared to the thermally treated **samples (Table 2)**.

Chemical profile of orange juice samples ^{1}HNMR

The spectra of the analyzed OJ samples (**Figure 3**) were dominated by resonances especially from amino acids, sugars (glucose, fructose and saccharose), organic acids and other secondary compounds as ethanol and ethyl acetate. Among these, 9 compounds (**Table 2**) clearly gave diagnostic signals in the NMR spectrum without overlapping, which permitted an accurate determination of their concentrations (g/L), so they were selected as marker peaks to explore composition changes throughout different stabilization processes on OJ.

Compared to UNT sample, HPP and all thermal treatments (except for MP) led to a significant ($p<0.05$) decrease of all selected marker peaks, mainly including sugars (alpha- and beta-glucose, beta-fructose, and sucrose) and amino acids, which are suggested to play a significant role in non-enzymatic browning reactions of thermal treated OJ (Pham et al., 2021). Results agree with SP values (**Table 1**) with significant lower values for all thermally treated samples. Lower pulp content means that suspended pulp was damaged by the treatment and its content released in the serum. OH, and

HCHE presented low SP value but probably reducing sugars were consumed by Maillard reaction more than in MP due to the lower treatment temperature in the latter **(Rattanathanalerk et al., 2005).** As previously discussed, HCHE presented the highest C_0 value and the lowest content of fructose (**Table 2**) as it is recognized as the main precursor of reactive carbonyl species, indicating its important role in the Maillard reaction (Paravisini and Peterson, 2019). Overall, HCHE and HPP are the treatments that mostly caused the loss of nutrients in OJ, likely due to degradation reactions. On the other hand, MP samples showed significant ($p<0.05$) greater concentrations of all marker compounds. This is probably because mild thermal treatment processes promoted the solubilization of the water-soluble compounds without leading to their degradation due to the mild temperatures and short time**. On the contrary, ethanol, ethyl acetate, D-alanine did not show significant differences for UNT, HCHE and MP samples ($p>0.05$); however, they significantly differed from HPP and OHMIC (Table 2).** Vervoot et al., (2011) **reported** that no significant difference or impact on sugars after HPP and pasteurization. So, also considering the previous observations from color analysis, these results **generally suggest** that HCHE and HPP treatments are mainly responsible to affect the visual and chemical/nutritional profile of the final product.

Sensorial analyses

Consumer discriminant test **demonstrated** that all treated samples were significantly recognized ($p<0.05$) from UNT, by 23/23 panellists, by 21/23 and by 17/23 for OH, HCHE and HPP, respectively. To better understand the most important descriptors responsible for the differences, QDA scores were analysed (**Table 3**): among all considered descriptors, orange aroma, cooked aroma, sweetness, cooked taste of thermally treated OJ samples **were** significantly different (in almost all the cases) from UNT ($p<0.05$). HPP samples showed a similar sensory profile **when** compared with UNT, showing only a **significant difference ($p<0.05$) in terms of orange aroma. A previous study (Leizerson and Shimoni, 2005a) reported results on OJ sensory profile showing a similar**

flavour profile for fresh and ohmic-heated OJ and they were not distinguishable by panellists. However, in this study $F_{90}^{6.7} = 0.83$ significantly lower compared to our study and probably for this reason ohmic heating resulted favourable. Moreover, by considering overall liking results, UNT resulted the most appreciated together with HPP, while on the contrary OH resulted the less appreciate (**Table 3**). **This result is in agreement with Parish (1998) which reported that panellists generally perceived the flavours of high pressure treated juices to be significantly closer to that of fresh one than flavours of thermally treated ones.** Three direct comparisons between treated samples were also performed: OH vs. HPP (17/23), HCHE vs. HPP (23/23), and OH vs. HCHE (15/23). In all assessments, untrained panellists were able to significantly ($p<0.05$) recognize samples confirming significant differences obtained in QDA (**Table 3**). **On the basis of this result, HCHE technology seems not favourable with respect to sensorial profile of treated OJ.**

Conclusions

This study aimed to evaluate the effect of traditional and emerging stabilization technologies on orange juice (OJ) quality characteristics. **Fresh O**J was compared with **treated OJ** by MP, HCHE, OH, and HPP. The results highlighted significant differences, in terms of physical (viscosity, colour), chemical (mainly total phenolic content and total antioxidant activity, sugar and ascorbic acid content), and sensory parameters of treated OJ samples compared to fresh juices. Among the evaluated treatments, HPP showed to be the best processing technology if compared to fresh OJ quality characteristics. HPP juice showed a considerably higher sensory rating if compared to the other treatments, and similar sensory characteristics to the untreated juice. Conversely OH did not show any significant and strong advantage if compared to traditional treatments (HCHE, MP), in terms of OJ quality parameters. MP is the treatment that better preserved the chemical profile if compared to the untreated orange juice.

Conflict of interest

The Authors declare that there are no conflicts of interest

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