Food and Bioprocess Technology (2022) 15:795–805
https://doi.org/10.1007/s11947-022-02782-8

ORIGINAL RESEARCH

Check for updates

Comparison of Different Technologies (Conventional Thermal Processing, Radiofrequency Heating and High-Pressure Processing) in Combination with Thermal Solar Energy for High Quality and Sustainable Fish Soup Pasteurization

Israel Muñoz[1] · David A. Baptista de Sousa[2] · Maria Dolors Guardia[1] · Carlos J. Rodriguez[2] · Maria Leonor Nunes[3] · Helena Oliveira[3,4] · Sara C. Cunha[5] · Susana Casal[5] · António Marques[4] · Ana G. Cabado[2]

Received: 25 October 2021 / Accepted: 5 February 2022 / Published online: 25 February 2022

Abstract
In this study, the potential of innovative (radiofrequency (RF) heating, high-pressure processing (HPP)) in combination with a renewable technology thermal solar energy (TSE)) to pasteurize fish soup was investigated. The performance of these technologies was compared to a conventional thermal treatment (CTT) using tubular heat exchangers. Thus, the impacts of these technologies on the product quality and microbiological quality as well as on water and energy consumption were analysed. RF and HPP technologies produced similar results when compared to CTT. The main differences were found in colour (higher colour stability in HPP), lipid oxidation (HPP had slightly higher TBARs values) and sensory analysis (RF: best appearance; HPP: best odour, texture and taste). TSE and RF together can save up to 70% of energy, whereas HPP can save up to 75% in water use. Despite the higher initial investment costs, these technologies are feasible alternatives for industrial pasteurization.

Keywords Fish soup · Radiofrequency heating (RF) · High-pressure processing (HPP) · Thermal solar energy (TSE) · Water and energy consumption

Introduction

Nowadays, consumers demand safe, fresh and minimally processed food products with excellent sensory properties and sustainable food production. The existence of some undesirable nutritional and sensory effects of conventional processing technologies has prompted many researchers to explore alternative treatments and/or non-thermal processing technologies (Atuonwu et al., 2018). There is also a growing interest from researchers and companies to incorporate renewable energy sources in the industrial processes (Farjana et al., 2018) because of its pivotal role in the EU Green Deal policy.

The food industry consumes large quantities of water and energy. Process heating, refrigeration and freezing are responsible for 75% of all energy consumed (Compton et al., 2018). The seafood processing industry has a high environmental impact due to the production of effluents, solid residues, and water and energy consumption. The reduction of energy and water use without compromising the characteristics of the final product represents a big challenge. Radiofrequency (RF) and high-pressure processing (HPP) are some of the innovative technologies that may contribute to this purpose. On the other hand, renewable energies (wind, sun, biomass, etc.) (i.e. thermal solar energy (TSE)) can reduce the use of fossil energies, which can contribute to decarbonising the economy.

✉ Israel Muñoz
israel.munoz@irta.cat

[1] IRTA - Food Quality and Technology Program, Finca Camps i Armet, 17121 Monells, Girona, Spain

[2] ANFACO-CECOPESCA, Campus University 16, 36310 Vigo, Spain

[3] CIIMAR, Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Terminal de Cruzeiros Do Porto de Leixões, Av. General Norton de Matos S/N, 4450-208 Matosinhos, Portugal

[4] Division of Aquaculture and Upgrading, IPMA, I.P., Portuguese Institute for the Sea and Atmosphere, Av. Alfredo Magalhães Ramalho 6, 1495-165 Lisboa, Portugal

[5] LAQV-REQUIMTE, Laboratory of Bromatology and Hydrology, Faculty of Pharmacy, University of Porto, R. Jorge de Viterbo Ferreira 228, 4050-313 Porto, Portugal

RF heating is based on the absorption of electromagnetic waves in the range of 10–300 MHz. Although similar to microwaves (MW), RF heating is more uniform and has a higher penetration depth because of the lower frequency range of the waves (Altemimi et al., 2019). As heat transfer is fast, nutrient, vitamin and flavour losses are minimized (Rosnes et al., 2011). RF has a high heating efficiency, similar to MW heating, minimizing energy losses (Ahmed & Ramaswamy, 2007), as energy is applied directly to the food product.

HPP is an emerging food preservation technique that uses pressure (100–600 MPa) instead of heat, thus preserving the nutritional and sensory properties (Gao et al., 2016). HPP has been approved by the US Food and Drug Administration, as a non-thermal pasteurization technology. It is an alternative to conventional thermal techniques because it can inactivate pathogenic and spoilage microorganisms (Campus, 2010) and enzymes, increasing shelf-life and guaranteeing the food safety of the product without the thermal consequences (Koutchma, 2014). HPP is considered a clean technology because it only requires electrical energy and water for food processing and does not produce waste residues (80% of the water is recycled at the end of each processing cycle) (Bermúdez-Aguirre & Barbosa-Cánovas, 2011).

Thermal solar energy (TSE) obtains energy from solar radiation, reducing the need for fossil energy sources in industrial processes. TSE has a conversion rate of around 70% (Jamar et al., 2016). The main potential for application is cleaning, washing, heating, pasteurization and sterilization (Farjana et al., 2018), with temperatures ranging from 45 to 300 °C. However, the performance of the system is constrained by the weather conditions (temperature, solar radiation, wind).

Many studies show that innovative technologies such as RF (or MW) or HPP improve the quality of processed products, obtaining products with quality closer to that of fresh products, when compared to thermally processed samples (conventional technology) (Benlloch-Tinoco et al., 2014; Marszałek et al., 2015; Yi et al., 2016). Moreover, these technologies offer a high potential for sustainable food production increasing energy efficiency (Panda et al., 2021) and minimizing water use. However, only few studies have analysed together the impact of these innovative technologies (considering RF a technology similar to MW) on product quality and energy and/or water utilization: HPP and MW in ready-to-eat meals (Pardo & Zufía, 2012), HPP and conventional heating in fruit juices (Sampedro et al., 2014); HPP and thermal pasteurization of orange juice (Cacace et al., 2020), conventional heating and microwaves (MW) in milk (Graf et al., 2020); and conventional heating, HPP and MW in orange juice (Atuonwu et al., 2020). Continuous RF, HPP and conventional heating have never been compared in the processing of liquids or semi-liquids, and more specifically, in soups. Moreover, there are very few studies on the use of RF in the processing of this type of products.

The objective of this study is to address the research gap which was to understand if these innovative technologies (RF, HPP) can be used to achieve significant reductions in energy and water consumption with respect to conventional processing while maintaining/improving the microbiological quality and quality of seafood products. Hence, a fish soup with a commercial shelf-life of 28 days (pasteurized and chilled) was used as a model since it can be processed with all the technologies described. Moreover, the potential of TSE as an alternative source of thermal energy was also studied.

Material and Methods

Soup Sample

The fish soup was prepared using a commercial fish powder broth widely available in the market (CHOVI, Benifaio, Spain). A commercial product was selected instead of a fresh one because of the large amounts of powdered soup needed for the experiments and to maintain the homogeneity of the product. The labelled nutritional composition of the powder was 7.2% fats, 26.2% carbohydrates, 9.9% proteins and 55.7% salt, with approximately 4.7% of fish. The soup was prepared by mixing the powder (50 g/l) and tap water following the supplier's recommendations. For each trial, 200 l of soup was prepared for CTT, RF, TSE and 22 l for HPP.

Pasteurization Conditions

Conventional Thermal Treatment (CTT)

CTT was performed at the Institute of Agrifood Research and Technology (IRTA) (Monells, Spain), in a 2-stage tubular heat exchanger built by INOXPA (Banyoles, Spain) (Fig. 1 left). The heat was provided by a steam generator ATTSU TECNIVAP (Celrà, Spain) or the TSE ("Thermal Solar Energy (TSE)"). The system processed 200 l of soup/h with a set-point temperature of 114 °C and a holding time of 5.45 s. After heating, the soup was cooled down in two heat exchangers, the first with tap water (15 °C) (800 l/h) and the second with glycol at −5 °C. Before processing, the equipment was sanitized with hot water at 80 °C for 0.5 h and, after processing, using a combination of caustic soda, nitric acid and hot water at 80 °C for 0.5 h. The thermal treatment was targeted to destroy spores of the psychrophile non-proteolytic *Clostridium botulinum* (group II) to obtain refrigerated processed foods with extended durability (Peck, 1997). To this purpose, a minimum cumulative total lethality equivalent to $P^{z}_{T_{ref}} = 10min$ was needed to achieve 6 log reduction of non-proteolytic *C. botulinum* spores (FDA, 2011):

Fig. 1 Tubular heat exchanger (left) and RF equipment (right)

$$P = \int_{t=0}^{t=t_{total}} 10^{\left(\frac{T-T_{ref}}{Z}\right)} dt \quad (1)$$

Where P is the cumulative total lethality value (min), T is the temperature of the treatment (°C), T_{ref} is the reference temperature (90 °C) at which the thermal resistance ($Z = 10$ °C) has been determined, and t is the holding time after reaching the temperature of the treatment (min). The holding time was given by the flow rate of soup and the diameter and length of the tube.

Radiofrequency (RF)

Soup was pasteurized using an equipment (45 kW EVO RF) from CARTIGLIANO Spa (Catigiliano, Italy) working at 27.12 MHz with a maximum RF power of 30 kW (Fig. 1 right) at IRTA. This equipment processed 200 l/h but it was only able to raise the soup temperature by 50 °C for this product in about 2 s. Due to this limitation, the soup was preheated at 65 °C using one stage of the tubular heat exchanger used in the CTT trials. After processing, the soup was cooled down and the facilities sanitized and cleaned as described for CTT. The set-point temperature was 115 °C and the holding time was 4.54 s. The temperature was determined using the same procedure described for CTT.

High-Pressure Processing (HPP)

HPP pasteurization was performed at ANFACO-CECOPESCA (Vigo, Spain) employing a HIPERBARIC H55 (Burgos, Spain), with a coupled Lauda Ultracool UC-0060/0240 cooling system (Fig. 2). The product was placed in 0.5 l polyethylene bottles with a polypropylene cap for processing. Twenty-two litres of soup was processed per batch. Different combinations of time and pressure were tested on the product (data not shown). The best combination (microbiological quality and product quality, etc.) corresponded to 2 cycles of 5 min at 5200 bars, with an overall processing time of 10 min. HPP tests were performed at room temperature. According to the preliminary results, for a given pressure, 2 cycles of 5 min were more effective at eliminating microorganisms than a 10-min cycle. Pressures greater than 500 MPa guaranteed the inactivation of enzymatic processes and microorganisms.

Thermal Solar Energy (TSE)

TSE was obtained from a solar collector field of 30 solar panels (Fig. 3), organized in 6 batteries of 5 vacuum tube collectors (Buderus SKR12, Wetzlar, Germany) with a surface of 2.57 m^2/collector located in IRTA. The energy was transferred to a tank with a capacity of 4.5 m^3 of water, directly feeding the tubular heat exchangers with hot water. In case the temperature of the buffer tank dropped 3 °C below the set-point of the buffer tank, the steam generator added the necessary heat through a heat exchanger. TSE was used as a source of thermal energy in CTT (TSE-CTT) and RF (TSE-RF) treatments. The treatment temperature was the same as described for CTT and RF treatments. The set-point temperatures of the buffer tank were 125 °C for TSE-CTT and 90 °C for TSE-RF. For TSE-RF, 65 °C was needed for preheating the soup in the heat exchanger (no heat was needed in the RF equipment) and 80 °C for cleaning with hot water. TSE experiments were conducted in summer (7.6 kWh/day m2 of solar radiation).

Fig. 2 HPP Hiperbaric H55 equipment

Analytical Methods

Storage Conditions and Sampling

Three independent experiments were performed for CTT, RF and HPP and the samples were stored in 50-mL sterile tubes (VWR 525–602) for CTT and RF or 0.5-l polyethylene food-grade bottles, with a polypropylene cap for HPP at 4 °C. At days 0 (control), 1, 7, 14, 21 and 28, samples were taken for analyses. Analysis of the control soup and day 1 soup was carried out right before/after processing, respectively. Samples for sensory analysis were obtained at day 1 and placed in 500-ml glass laboratory bottles (Duran Wheaton Kimble) at 4 °C for 5 days to ensure product stabilization (aroma and taste). All the analyses were performed in triplicate.

TSE-CTT and TSE-RF treatments were equivalent to CTT and RF. Only the source of thermal energy changed but did not affect the processing. Therefore, no physicochemical and microbiological analyses were carried out.

Proximate Composition

Moisture was determined by oven drying at 105 ± 2 °C until reaching constant weight. Protein was determined with the Kjeldahl method, the total fat with the Soxhlet extraction method (AOAC, 2005). Carbohydrates plus fibre were determined by difference. All analyses were performed on day 1.

Colour

Colour of the soup samples (CTT, RF), i.e. lightness/darkness (L*), redness/greenness (a*) and yellowness/blueness (b*) (CIE, 1976), was measured using a colorimeter (Minolta Chroma Meter CR-400, Tokyo, Japan). The illuminant used was D65 with 2°. In HPP processed samples, it was used a PCE colorimeter model CSM2 with a silicon photoelectric diode as sensor, an aperture of 8 mm and a geometry of 45° (0/45). Two different colorimeters were used as analysis was performed at different locations (IRTA and ANFACO). Results are expressed in colour differences ($\Delta E = \sqrt{(\Delta \mathrm{L})^2 + (\mathbf{\Delta a})^2 + (\mathbf{\Delta b})^2}$). The ΔE was calculated between control at day 0 (reference value) and processed samples (CTT, RF and HPP) during chilled storage.

pH

For CTT and RF treatments (analysis performed at IRTA), the pH was measured with an immersion probe (Testo 206-pH2, Lenzkirch, Germany). For HPP (analysis performed at ANFACO), a HACH pH metre (Loveland, USA), model pH3, with pH SensION + 5011 T electrolyte sensor and Pt 1000 temperature sensor was used. The analyses were performed based on pH stability at room temperature (21 °C).

Lipid Oxidation

Lipid oxidation was determined by using the 2-thiobarbituric acid index (TBA). The procedure was based on the Vyncke method modified by Ke et al. (1984), from a trichloroacetic acid (7.5%) extract. Results were calculated using a standard curve prepared with different concentrations of 1,1,3,3-tetraethoxypropane.

Microbiological Quality

Microbiological analyses were performed at day 0, 1 and 28 of chilled storage for all treatments and day 0 and 28 for the control soup. For CTT and RF treatments (performed at IRTA), *Enterobacteriaceae* was incubated at 37 ± 1 °C for 24 h and enumerated on REBECCA base agar (ISO 16140). Psychrophiles were cultivated and enumerated on a plate count agar (PCA) after 24 h at 22 ± 1 °C. Lactic acid bacteria were incubated in anaerobic conditions at 30 ± 1 °C for 72 h and enumerated on Man, Rogosa and Sharpe agar (MRS)

Fig. 3 Solar collectors

(ISO 15214). *Enterococcus* was incubated at 35 ± 1 °C for 48 h and enumerated on m-enterococcus agar (ISO 7899–2). For HPP treatments (performed at ANFACO), *Enterobacteriaceae* was incubated in a violet red bile glucose agar (VRBG) at 37 ± 1 °C for 24 h. Psychrophiles were enumerated by plate count in PCA medium after 7 days/5 °C and lactic acid bacteria by plate count in an MRS medium at 30 ± 1 °C for 72 h. *Enterococcus* (Lancefield Group D *Streptococcus*) was detected by plate count in a Bile Esculin Agar (BEA) medium after 24 h/37 °C. The presence of the most important pathogens (*Salmonella* sp., *Listeria* sp. (Enzyme Linked Immunofluorescent Assay) and *Staphylococcus aureus* (ISO 6888–2)) was also evaluated during preliminary tests.

Sensory Evaluation

A preference ranking test was used (ISO 8587). The ranking test evaluated the following attributes by preference (from the highest to the lowest): appearance, odour, texture and taste. No sensory scale was used. Panellists were asked to order the samples based on preference. Samples were ranked "1", "2" and "3", where "1" indicated the sample most preferred and "3" the less preferred. Sensory analysis was performed by a panel with 13 trained panellists. Rankings provided by panellists were summed for each attribute and treatment. Samples were prepared identically and presented codified with three-digit random numbers sequentially in 3 disposable plastic glasses in a random order, preheated for 2 min at 60–70 °C. Whenever possible, the panellists indicated the organoleptic characteristics. Samples were stabilized for 5 days after processing before evaluation.

Energy and Water Process Evaluation

All technologies were evaluated in terms of energy (kWh) and water consumption (m^3). Calculations were based on an 8-h shift and 225 working days/year. For CTT and RF, 7 h was considered for actual production time and 1 h for cleaning, whereas 8 h was considered production time for HPP with 3 batches/h 24 batches/day.

For CTT and RF, annual production was 337.5 m^3/year (200 l of soup/h–1400 l of soup/day) and for HPP 118.8 m^3/year (22 l of soup/batch–528 l soup/day). Results were expressed in kWh/m^3 of soup and m^3 of water/m^3 of soup. The costs of energy and water were estimated at 0.15 €/kWh and 1.5 €/m^3 of water, respectively. Energy use for CTT and RF (with/without TSE) was recorded during 1 h of processing. Data on energy and water consumption was obtained from existing metres that were placed at different points in the equipment and data collected manually from other measuring systems installed for this investigation.

Statistical Analysis

Analysis of variance and Tukey's test was performed to determine significant differences between technologies and storage times using Statistical Program for Social Science (SPSS v23) software (IBM, Chicago, IL, USA). Significance differences were defined at $p \leq 0.05$. For the sensory classification by ranking, ranking was analysed via Friedman's test; rank-sums were calculated and compared using least-significant-differences (LSD) (Lawless & Heymann, 2010) in order to decide which groups are significantly different from each other (Lawless & Heymann, 2010) at $p \leq 0.05$.

Results and Discussion

Proximate Composition

As expected, no significant differences were found for most of the components, indicating that soup nutrients were similarly affected by all treatments (Table 1). The small significant differences observed for ash and carbohydrates can be explained probably by slight differences in the mixing ratios during preparation of the samples. These small differences do not have any impact on the results of this study.

Colour

According to Morkrzycki and Tatol (2011), for ΔE values from 1 to 2, differences can only be perceived by an experienced observer, from 2 to 3.5, an unexperienced observer can observe small differences; from 3.5 to 5, differences are noticeable, and for values higher than 5, two different colours are perceived. ΔE values between 4 and 5 were observed between control and RF treated samples (Table 2), whereas for CTT, the values were slightly lower (between 3 and 4.5), indicating in both cases noticeable colour differences. For HPP samples, ΔE values were below 2. Thus, differences in colour were difficult to perceive by an unexperienced observer. For CTT and RF samples, L* (results not shown) increased during processing, showing a lighter colour. For HPP and in some degree for CTT and RF samples, b* tended to decrease over time. Thus, samples turned yellower over time.

No studies in the scientific literature have been found for RF and HPP in fish soups. However, MW heating and HPP seem to minimize changes in colour in liquid or viscous products, such as kiwifruit or strawberry puree (Benlloch-Tinoco et al., 2014; Marszałek et al., 2015) for MW or in fruit juices and purees for HPP (Landl et al., 2010; Yi et al., 2016, 2017). The results for RF are somewhat unexpected as the colour seems not to improve with respect to CTT.

Table 1 Proximate composition (in g 100 g^{-1}) of fish soup. Results are given as mean ± standard deviation ($n = 3$)

	Elemental composition		
	CTT	RF	HPP
Moisture	95.60 ± 0.11a	95.41 ± 0.12a	95.26 ± 0.23a
Protein	0.41 ± 0.04a	0.40 ± 0.03a	0.43 ± 0.04a
Fat	0.28 ± 0.04a	0.30 ± 0.09a	0.21 ± 0.04a
Ash	2.69 ± 0.05a	2.70 ± 0.15ab	2.82 ± 0.04b
***Carbohydrates + fibre**	1.02 ± 0.05a	1.20 ± 0.12ab	1.26 ± 0.08b

*Carbohydrates plus fibre were determined by difference. The different lowercase letters (a, b) indicate significant differences ($p \leq 0.05$) between processing conditions

Table 2 Colour differences (ΔE) between control soup (day 0) and soup processed with CTT, RF and HPP during chilled storage for up to 28 days

Storage day	ΔE		
	CTT	RF	HPP
1	3.02 ± 0.68abA	4.11 ± 0.2aA	1.61 ± 0.83bA
7	3.64 ± 1.24aAB	4.10 ± 0.79aAB	1.03 ± 0.46bA
14	4.55 ± 0.31aB	5.12 ± 0.31aB	0.65 ± 0.52bA
21	3.99 ± 0.24aAB	3.99 ± 0.25aA	0.34 ± 0.46bA
28	3.96 ± 0.50aAB	4.97 ± 0.24aB	0.61 ± 0.49bA

Results are given as mean ± standard deviation ($n = 3$). The different lowercase letters (a, b) indicate significant differences ($p \leq 0.05$) between processing conditions. Different uppercase letters (A, B, C) indicate significant differences between the storage days ($p \leq 0.05$)

However, in a recent published study in kiwi (Lyu et al., 2018), RF and CTT processed samples do not present very significant differences in colour over time. One possible reason for this result is that the processing times for both technologies (RF and CTT) are not considerably different and heating might have a similar impact on the colour.

For HPP, the differences found are explained by the fact that HPP is not a thermal treatment and thus colour is not affected by changes caused by temperature, namely Maillard reactions (Shashidhar et al., 2015). Other possible causes are the presence of oxygen in the recipients (HPP bottles had no or minimal headspace) that can induce oxidative changes in coloured nutrients, non-enzymatic reactions, incomplete inactivation of enzymes or degradation and polymerization of the available pigments (Landl et al., 2010).

pH

The pH value increased significantly after processing for all the treatments (Table 3). The highest increase of pH was observed in HPP-treated samples resulting in a neutral fish soup, whereas the increase for CTT and RF was smaller, and samples were slightly more acidic. Since pH increase in HPP was observed immediately after processing, it does not seem to be attributed to enzymatic activity but rather by a probable reduction in dissolved CO_2 (Ludwig & Macdonald, 2005). The pH values observed in CTT and RF samples after processing were similar to those found in a shrimp soup (Shashidhar et al., 2015). After processing, fish soup did not show any significant change in the pH during the 28 days of the study, similarly to that found in a salmon soup at the same storage temperature (not pasteurized) (Mol, 2005).

Lipid Oxidation

During thermal pasteurization, the flavour compounds and precursors can change due to different physicochemical

Table 3 pH of control soup samples (day 0) and soup processed with CTT, RF and HPP during chilled storage for up to 28 days

Storage day	pH		
	CTT	RF	HPP
0 (control)	6.60 ± 0.07A		
1	6.76 ± 0.03aBC	6.85 ± 0.08aB	7.09 ± 0.07bB
7	6.74 ± 0.04aB	6.82 ± 0.11aB	7.11 ± 0.03bB
14	6.66 ± 0.10aAB	6.78 ± 0.08aB	7.03 ± 0.08bB
21	6.69 ± 0.03aAB	6.74 ± 0.12aAB	7.00 ± 0.01bB
28	6.64 ± 0.06aAB	6.73 ± 0.13aAB	7.08 ± 0.01bB

Results are given as mean ± standard deviation ($n = 3$). The different lowercase letters (a, b) indicate significant differences ($p \leq 0.05$) between processing conditions. Different uppercase letters (A, B, C) indicate significant differences between the storage days ($p \leq 0.05$)

reactions. Regarding the fish soup, fat oxidation is expected to be the main flavour precursor due to the formation of volatile aldehydes and ketones which are important components of the oxidized flavour. In the present work, a value of 0.35 mg of malondialdehyde MDA l^{-1} was observed in the control soup (Table 4), indicating a low degree of oxidation of the powdered soup (4.7% fish powder dry extract with a fat level of 0.21–0.30% in solution). Immediately after processing, differences in TBARs content were observed between treatments, with significantly lower values in CTT and RF samples ($p < 0.05$) compared to HPP. This result can be a consequence of the processing temperature (115 °C) which may have induced the loss of some oxidation products (Xie et al., 2022). During storage at 4 °C for 28 days, the TBARs values of CTT and RF samples remained constant and with values similar to those found in thermally processed shrimp soup (Shashidhar et al., 2015). In these processes, the TBARs values were below 1 mg MDA l^{-1}, indicating an “excellent” quality in terms of lipid oxidation (Tolasa et al., 2012).

Table 4 TBARs contents of fish soup control and soup processed with CTT, RF and HPP during chilled storage for up to 28 days

Storage day	TBARs (mg MDA·l^{-1})		
	CTT	RF	HPP
0 (control)	0.35 ± 0.11A		
1	0.16 ± 0.09aA	0.26 ± 0.10aA	0.52 ± 0.08bA
7	0.24 ± 0.11aA	0.13 ± 0.04aB	1.83 ± 0.28bC
14	0.23 ± 0.01aA	0.36 ± 0.11aA	2.03 ± 0.35bC
21	0.22 ± 0.08aA	0.12 ± 0.06aB	1.83 ± 0.28bC
28	0.29 ± 0.10aA	0.22 ± 0.06aAB	0.92 ± 0.19bB

Results are given as mean ± standard deviation ($n = 3$). The different lowercase letters (a, b) indicate significant differences ($p \leq 0.05$) between processing conditions. Different uppercase letters (A, B, C) indicate significant differences between the storage days ($p \leq 0.05$)

Table 5 Microbiological results of fish soup control and soup processed with CTT, RF and HPP during chilled storage for up to 28 days

	Storage day	Microbiological analyses (cfu ml^{-1})			
		Control	CTT	RF	HPP
Psychrophiles	0	1.4×10^3	< 10	< 10	< 10
	1	1.4×10^3	< 10	< 10	< 10
	28	6.3×10^6	< 10	< 10	< 10
Enterobacteriaceae	0	< 10	< 10	< 10	< 10
	1	< 10	< 10	< 10	< 10
	28	< 10	< 10	< 10	< 10
Lactic Bacteria	0	13	< 10	< 10	< 10
	1	13	< 10	< 10	< 10
	28	< 10	< 10	< 10	< 10
Enterococcus	0	< 10	< 10	< 10	< 10
	1	< 10	< 10	< 10	< 10
	28	< 10	< 10	< 10	< 10

N.D, not determined

The HPP samples underwent a significant increase in the TBARs after the first week of storage, reaching values close to 2 mg MDA l^{-1}, which decreased to 0.92 mg MDA l^{-1} after 4 weeks. HPP processing induced a slight oxidation degree of the lipids that generate MDA, the main compound that reacts with thiobarbituric acid (TBA), partially due to the low-fat content of the raw material used. It has been pointed out that lipid oxidation is a problem for HPP (Campus, 2010). HPP treatments could activate some enzymes due to their reversible configuration after inactivation. TBARs analyses on several fishery products processed with HPP showed an increase in lipid oxidation (Erkan et al., 2011; Lakshmananet al., 2005; Senturk & Alpas, 2013). On the other hand, the TBARS decrease observed between 21 and 28 days of storage may indicate that some oxidation products participated in other biochemical reactions as a substrate (Xie et al., 2022).

Microbiological Quality

After 28 days of refrigerated storage, all the treatments guaranteed the microbiological quality of the soup for the analysed parameters (Table 5). Psychrophilic bacteria increased in control soup samples, reaching counts greater than 6.0×10^6 cfu ml^{-1} after 28 days of chilled storage, around the acceptable limit (EC, 2005). After processing (day 1), the counts of psychrophiles were significantly reduced and after 28 days of storage at 4 °C, values were still < 10 cfu ml^{-1}. Similar results were obtained for *Enterobacteriaceae*, lactic acid bacteria and *Enterococcus*. The first HPP cycle inactivates vegetative cells of microorganisms present in the

Table 6 Ranking test results of sensory analysis carried out on fish soup processed under CTT, RF and HPP after 5 days since pasteurization

Parameter	R Sum			*F* value
	CTT	RF	HPP	
Appearance	36a	19b	23b	12.154*
Odour	32a	28a	18b	8.000*
Mouthfeel	29.5a	31a	17.5b	8.423*
Flavour	29a	31a	18b	7.538*

R Sum: total sum of the ranking test for the 13 panellists per evaluated attribute. Lower sum is considered to be the best sensory evaluation (preference ranking). For the Friedman's test, (*) indicates significant differences ($p \leq 0.05$) processing technologies. For LSD, the different lowercase letters (a, b) indicate significant differences ($p \leq 0.05$) between processing technologies

soup and, at the same time, HPP induces the germination of spores from spore-forming bacteria, which are inactivated by the second HPP cycle (Wuytack et al., 1997). *Salmonella* sp., *Listeria* sp., and *Staphylococcus aureus* were not detected in the soup.

Sensory Evaluation

According to the preference ranking carried out, using the Friedman test, there were significant differences in the appearance of the soup samples (Table 6), with CTT being different from RF and HPP; in addition, significant differences in odour, texture and flavour attributes were also observed. In general, panellists preferred soup samples processed with HPP, except for the appearance. The colour of the RF samples was described as darker and more intense, but it was regarded as a positive attribute.

Some panellists perceived the mouthfeel of the RF samples as more aqueous, which was not corroborated with the instrumental viscosity analysis (data not shown). In general, the odour of the HPP samples was described as more balanced. The flavour of the RF samples was scored with higher overall intensity when compared with those obtained by CTT. In addition, RF samples were characterized by an off-flavour similar to those of commercial soups. The flavour of the CTT samples was described as the least intense, indicative of sensory losses occurred during thermal process, as mentioned previously for volatiles. In summary, the HPP-treated soups presented the best sensory attributes (Table 6), regarded as more similar to unprocessed soup. No results have been found in the literature for fish soup processed with these technologies. However, there are many examples of the better sensorial quality of liquid or semi-liquid products in the literature processed with HPP or MW but not for RF. For MW, kiwifruit and strawberry puree (Benlloch-Tinoco et al., 2014; Marszałek et al., 2015) or pesto sauce (Klug, Collado, et al., 2018) and for HPP, blueberry and apple juice (Barba et al., 2013; Yi et al., 2017). HPP and MW were directly compared for processing two different types of hummus (Klug et al., 2018); each technology presented the best sensorial quality in one of the hummus.

Energy Process Evaluation

The highest energy consumption during processing was recorded for CTT and the lowest for TSE-RF (75% lower) (Table 7). For TSE-RF, 100% of the thermal energy was provided by the solar collectors and the steam generator was not used. RF also showed a lower energy consumption, around 25% lower than for CTT, whereas HPP and TSE-CTT was only slightly lower. For TSE-CTT, only a small fraction (around 25%) came from the solar collectors with the steam generator providing most of the energy due to the set-point temperatures in the buffer tank (125 °C vs. 90 °C for TSE-CTT and TSE-RF, respectively). For this reason, TSE-CTT was only able to achieve a small reduction (around 10%).

CTT and TSE-CTT presented the highest energy consumption during sanitation, whereas TSE-RF presented the lowest value (20% of CTT). During cleaning, the energy consumption was very similar for CTT and RF, whereas for TSE-CTT and TSE-RF, those values were around 25% of CTT, as the solar system was able to provide the necessary thermal energy during cleaning (80 °C). For HPP, no special sanitation and cleaning operations were required and energy was not needed.

When comparing all the technologies on annual basis and for an equivalent production, the best technology was TSE-RF. However, TSE-RF is limited to sunny days. Trials conducted in winter showed that solar collectors were able to reach temperatures above the pasteurization temperatures. However, the buffer tank was unable to reach the set-point temperature due to the freezing temperatures. In areas with warmer temperatures and with more solar radiation, TSE might be also used in winter, although this should be further investigated. HPP could be an alternative to TSE, as it presents a lower energy consumption than CTT.

Other studies show contradictory results for innovative technologies. For a ready-to-eat product (vegetables and fish), energy consumption of innovative technologies (HPP and MW) was higher than for conventional thermal processing (autoclave) (Pardo & Zufía, 2012). Similarly, a ninefold increase was found for HPP in orange juice (Sampedro et al., 2014) and a fivefold increase for the pasteurization of tomato and watermelon juice (Aganovic et al., 2017). However, for the pasteurization of orange juice (Atuonwu et al., 2018), HPP and MW had a slightly better energy efficiency than CTT. In another study by the same author (Atuonwu et al., 2020), the energy consumption of MW was slightly lower

Table 7 Energy use for processing (pasteurization) and cleaning using different technologies

	CTT	RF	TSE** (CTT)	TSE** (RF)	HPP
Energy processing (kWh /m^3)	419	326	383 (26%)	126 (100%)	407
Energy sanitation (kWh/process)	160	126	170 (23%)	26 (100%)	0
Energy cleaning (kWh/process)	47	48	12 (100%)	10 (100%)	0
Day (kWh/day)	793.6	630.4	718.2	212.4	216
Annual (kWh/year)	178,560	138,688	161,595	47,790	48,600
Annual equivalent* (kWh/year)	178,560	138,688	161,595	47,790	128,377
Cost (€/m^3)	85.02	67.54	76.95	22.76	61.05
Equivalent* annual cost (€)	26,784	20,803	24,239	7,169	19,257

*Equivalent annual production and cost were calculated considering for HPP the same production rate as for CTT, RF and TSE. **In () fraction of solar energy (%) over total thermal energy

than for CTT, similar to the results obtained in this study for CTT and RF, but HPP was higher than for any of the two technologies. Recently, Cacace et al. (2020) found a much lower energy consumption for HPP than for thermal processing technologies during pasteurization of orange juice. These contradictory results can be explained by the different production capacity of each equipment. Moreover, for HPP the energy consumption may change a lot depending on the combination of pressure and time, and this depends on the product and the logs of microbial inactivation. A good optimization of the processing conditions for HPP may save a lot of energy.

For TSE, Frey et al. (2015) achieved 81% savings of primary energy to heat up water process at 60 °C.

Water Process Evaluation

Water use (Table 8) was much lower for HPP than for CTT and RF. The reason for this result was that the water used for pressurization in HPP was recycled. Water was only added to make up for the water losses (15%). During processing, foodstuffs are packaged and sealed prior to processing. Thus, the water used for pressurization does not get contaminated.

Table 8 Water use for processing (pasteurization) and cleaning using different technologies

	CTT	RF	HPP
Water processing (m^3/h)	0.302	0.322	0.027
Water processing (m^3/m^3 soup)	1.51	1.61	0.41
Cleaning (m^3)	0.62	0.66	0
Day (m^3/day)	2.73	2.91	0.22
Annual (m^3/year)	614.3	655.7	48.6
Annual equivalent* (m^3/year)	614.3	655.7	60.8
Cost (€/m^3)	2.28	2.41	0.61
Equivalent annual cost (€)	921.5	983.6	211.4

*Equivalent annual production and cost were calculated considering for HPP the same production rate as for UHT, RF and TSE

Moreover, no cleaning was necessary under normal operation conditions for HPP. CTT needed slightly less water than RF, even though this difference could be explained by the variability in the experiments. TSE-RF might also save water, as steam was not used (losses during the generation and transportation). However, this could not be quantified. Other studies have found similar results to those obtained herein. Pardo and Zufía (2012) found lower water use for HPP than for thermal equivalent technologies (autoclave and MW). For orange juice pasteurization (Cacace et al., 2020), HPP reduced water consumption by over 93%. Graf et al. (2020) found that microwave heating resulted in a lower deposit formation on the heating section, which could help to reduce water use during the cleaning phase.

Conclusions

The results show that the innovative technologies tested (RF and HPP) were able to maintain (with the exception of lipid oxidation) or improve product quality in comparison to conventional thermal processing (sensory, etc.), while reducing energy and water use. In terms of nutritional composition and microbiological stability, RF and HPP technologies produced similar results when compared to the conventional technology. The main differences were found in colour (higher colour stability in HPP), lipid oxidation (HPP had slightly higher TBARs values), and sensory analysis (RF: best appearance; HPP: best odour, mouth-feeling and taste). From the point of view of sustainability, a combination of TSE and RF was able to save up to 75% energy, while HPP saves up to 75% water. Further experimental research is required to optimize the operational energy consumption of HPP processing and study the full potential of TSE.

Despite their savings on water and energy, the high investment costs (50–75% higher) of these innovative technologies remain a problem for the food industry. The increasing costs of fossil energies (i.e. natural gas) may increase the competitiveness and interest of these technologies in the future.

Author Contribution IM: supervision, investigation, writing — original draft. DABdS: investigation, writing — original draft. MDG: investigation, writing — original draft. CJR: investigation. MLN: conceptualization, investigation, writing — review and editing. HO: investigation, writing — review and editing. SCC: investigation, writing — review and editing. SC: writing — review and editing. AM: funding adquisition. AGC: investigation, writing — original draft.

Funding The research leading to these results received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 773400 (SEAFOOD^{TOMORROW}). This article reflects the views only of the authors and the European Union cannot be held responsible for any use, which may be made of the information contained therein. IRTA's authors have also received support from the CERCA Programme provided by the *Generalitat de Catalunya.* Sara Cunha has received support from the Fundaçao para a Ciencia e a Tecnologia (FCT) under grant number IF/01616/2015 and under the grant number UID/QUI/50006/2019 with funding from FCT and Ministério da Ciência, Tecnologia e Ensino Superior (MCTES).

Availability of Data and Material All data generated or analysed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Aganovic, K., Smetana, S., Grauwet, T., Toepfl, S., Mathys, A., Van Loey, A., & Heinz, V. (2017). Pilot scale thermal and alternative pasteurization of tomato and watermelon juice: An energy comparison and life cycle assessment. *Journal of Cleaner Production, 141*, 514–525.

Ahmed, J., & Ramaswamy, H. S. (2007). Microwave pasteurization and sterilization of foods. In M. S. Rahman (Ed.), *Handbook of Food Preservation* (pp. 691–712). CRC Press.

Altemimi, A., Aziz, S. N., Al-HiIphy, A. R. S., Lakhssassi, N., Watson, D. G., & Ibrahim, S. A. (2019). Critical review of radio-frequency (RF) heating applications in food processing. *Food Quality and Safety, 3*(2), 81–91.

AOAC. (2005). Official method of analysis. 18th Edition, Association of Officiating Analytical Chemists, Washington DC, Method 935.14 and 992.24.

Atuonwu, J. C., Leadley, C., Bosman, A., Savvas, A. T., Lopez-Quiroga, E., & Fryer, P. J. (2018). Comparative assessment of innovative and conventional food preservation technologies: Process energy performance and greenhouse gas emissions. *Innovative Food Science & Emerging Technologies, 50*, 174–187.

Atuonwu, J.C., Leadley, C., Bosman, A., & Savvas A.T. (2020). High pressure processing, microwave, ohmic and conventional thermal pasteurization: Quality aspects and energy economics. *Journal of Food Process Engineering*, *43*(2), e1328.

Barba, F. J., Esteve, M. J., & Frigola, A. (2013). Physicochemical and nutritional characteristics of blueberry juice after high pressure processing. *Food Research International, 50*, 545–549.

Benlloch-Tinoco, M., Igual, M., Salvador, A., Rodrigo, D., & Martínez-Navarrete, N. (2014). Quality and acceptability of microwave and conventionally pasteurised kiwifruit puree. *Food and Bioprocess Technology, 7*, 3282–3292. https://doi.org/10.1007/s11947-014-1315-9

Bermúdez-Aguirre, D., & Barbosa-Cánovas, G. V. (2011). An update on high hydrostatic pressure, from the laboratory to industrial applications. *Food Engineering Reviews., 3*(1), 44–61.

Cacace, F., Bottani, E., Rizzi, A., & Vignali, G. (2020). Evaluation of the economic and environmental sustainability of high pressure processing of foods. *Innovative Food Science and Emerging Technologies*, *60*, 102281.

Campus, M. (2010). High pressure processing of meat, meat products and seafood. *Food Engineering Reviews, 2*(4), 256–273.

CIE. (1976). Colourimetry: Official recommendations of the international commission on illumination. Publication CIE No. 15 (E-1.3.1). Boreau Central de la Commission Internationale De L'Eclairage, Paris.

Compton, M., Willis, S., Rezaie, B., & Humes, K. (2018). Food processing industry energy and water consumption in the Pacific North West. *Innovate Food Science and Emerging Technologies, 47*, 371–383.

EC (European Community). (2005). Commission regulation (EC) No. 2073/2005. Microbiological criteria for foodstuffs. *Official Journal, 338*, 1

Erkan, N., Üretener, G., Alpas, H., Selçuk, A., Özden, Ö., & Buzrul, S. (2011). Effect of high hydrostatic pressure (HHP) treatment on physicochemical properties of horse mackerel (Trachurus trachurus). *Food and Bioprocess Technology, 4*(7), 1322–1329.

Farjana, S. H., Huda, N., Mahmud, M. A. P., & Saidur, R. (2018). Solar process heat in industrial systems – a global review. *Renewable and Sustainable Energy Review, 82*(3), 2270–2286.

FDA. (2011). Pathogenic bacteria survival through cooking or pasteurization. In: Fish and Fishery Products: Hazards and Controls Guidance (4th Ed.) US Department of Health and Human Services. Food and Drug Administration. Center for Food Safety and Applied Nutrition.

Frey, P., Fischer, S., Drück, H., & Klemens, J. (2015). Monitoring results of a solar process heat system installed at a textile-company in Southern Germany. *Energy Procedia, 70*, 615–620.

Gao, G., Ren, P., Cao, X., Yan, B., Liao, X., Sun, Z., & Wang, Y. (2016). Comparing quality changes of cupped strawberry treated by high hydrostatic pressure and thermal processing during storage. *Food and Bioproducts Processing, 100*, 221–229.

Graf, B, Kapfer, T., Ostertag, F., & Hinrichs, J. (2020). New experimental set-up for testing microwave technology to continuously heat fouling-sensitive food products like milk concentrates. *Innovative Food Science & Emerging Technologies*, *65*, 102453.

ISO 6888–2. (1999). Microbiology of the food chain – horizontal method for the enumeration of coagulase-positive staphylococci (Staphylococcus aureus and other species) — part 2: Technique using rabbit plasma fibrinogen agar medium.

ISO 7899–2. (2000). Water quality – detection and enumeration of intestinal enterococci - part 2: Membrane filtration method. Geneva.

ISO 8587. (2010). Sensory analysis-methodology-ranking. Geneva.

ISO 15214. (1998). Microbiology of food and animal feeding stuffs — horizontal method for the enumeration of mesophilic lactic acid bacteria — colony-count technique at 30 degrees C. Geneva.

ISO 16140. (2016). Microbiology of food and animal feeding stuffs—protocol for the validation of alternative methods. Geneva.

Jamar, A., Majid, Z. A., Azmi, W. H., Norhafana, M., & Razak, A. (2016). A review of water heating system for solar energy applications. *International Communications in Heat and Mass Transfer, 76*, 178–187.

Ke, P. J., Cervantes, E., & Robles-Martinez, C. (1984). Determination of thiobarbituric acid reactive substances (TBARS) in fish tissue by an improved distillation-spectrophotometric method. *Journal of the Science of Food and Agriculture, 35*(11), 1248–1254.

Klug, T. V., Collado, E., Martínez-Sánchez, A., Gómez, P. A., Aguayo, A., Otón, M., Artés, F., & Artés-Hernández. (2018). Innovative quality improvement by continuous microwave processing of a faba beans pesto sauce. *Food and Bioprocess Technology, 11*, 561–571. https://doi.org/10.1007/s11947-017-2024-y

Klug, T. V., Martínez-Hernández, G. B., Collado, E., Artés, F., & Artés-Hernández, F. (2018). Effect of microwave and high-pressure processing on quality of an innovative broccoli hummus. *Food and Bioprocess Technology, 11*, 1464–1477. https://doi.org/10.1007/s11947-018-2111-

Koutchma, T. (2014). *Fundamentals of HPP technology*. Adapting high hydrostatic pressure (HPP) for food processing operations. Guelph: Academic press, Elsevier, 5–10.

Lakshmanan, R., Miskin, D., & Piggott, J. R. (2005). Quality of vacuum packed cold-smoked salmon during refrigerated storage as affected by high-pressure processing. *Journal of the Science of Food and Agriculture, 85*(4), 655–661.

Landl, A., Abadias, M., Sárraga, C., Viñas, I., & Picouet, P. (2010). Effect of high pressure processing on the quality of acidified Granny Smith apple purée product. *Innovation Food Science & Emerging Technologies, 11*, 557–564.

Lawless, H. T., & Heymann, H. (2010) Sensory evaluation of food principles and practices. 2nd ed. Springer; New York. (Food science text series). https://link.springer.com/book/10.1007/978-1-4419-6488-5I

Lyu, M., Peng, X., Wang, S., Yang, B., Wang, X., Yang, H., Xiao, Y., Baloch, A. B., & Xiaodong, X. (2018). Quality and consumer acceptance of radio frequency and traditional heat pasteurised kiwi puree during storage. *International Journal of Food Science and Technology, 53*(1), 209–218.

Ludwig, H., & Macdonald, A. G. (2005). The significance of the activity of dissolved oxygen, and other gases, enhanced by high hydrostatic pressure. *Comparative Biochemistry and Physiology Part a: Molecular & Integrative Physiology, 140*(4), 387–395.

Marszałek, K., Mitek, M., & Skąpska, S. (2015). Effect of continuous flow microwave and conventional heating on the bioactive compounds, colour, enzymes activity, microbial and sensory quality of strawberry purée. *Food and Bioprocess Technology*, *8*, 1864–1876. https://doi.org/10.1007/s11947-015-1543-7

Mol, S. (2005). Preparation and the self-life assessment of ready-to-eat fish soup. *European Food & Research Technology, 220*, 305–308.

Morkrzycki, W. S., & Tatol, M. (2011). Colour difference ΔE – a survey. *Machine Graohics & Vision International Journal, 20*(4), 383–411.

Panda, B. K., Panigrahi, S. S., Mishra, G., & Shrivastava, S. L. (2021). Microwave-assisted hydration of freshly harvested paddy (Oryza sativa L.): Process development based on soaking characterization and energy utilization. *Food and Bioproducts Processing, 14*, 1844–1856. https://doi.org/10.1007/s11947-021-02682-3

Pardo, G., & Zufía, J. (2012). Life cycle assessment of food-preservation technologies. *Journal of Cleaner Production, 28*, 198–207.

Peck, W. P. (1997). Clostridium botulinum and the safety of refrigerated processed foods of extended durability. *Trends in Food Science & Technology, 8*(6), 186–192.

Rosnes, J. T., Skåra, T., & Skipnes, D. (2011). Recent advances in minimal heat processing of fish: Effects on microbiological activity and safety. *Food and Bioprocess Technology, 4*, 833–848. https://doi.org/10.1007/s11947-011-0517-7

Sampedro, F., McAloon, A., Yee, W., Fan, X., & Geveke, D. J. (2014). Cost analysis and environmental impact of pulsed electric fields and high pressure processing in comparison with thermal processing. *Food and Bioprocess Technology, 7*, 1928–1937.

Senturk, T., & Alpas, H. (2013). Effect of high hydrostatic pressure treatment (HHPT) on quality and shelf life of Atlantic mackerel (Scomber scombrus). *Food and Bioprocess Technology, 6*, 2306–2318. https://doi.org/10.1007/s11947-012-0943-

Shashidhar, K., Biji, K. B., Ravishankar, C. N., Srinivasa-Gopal, T. K., & Joseph, J. (2015). Development of ready to drink iron fortified shrimp soup in retortable pouches. *Fishery Technology, 52*, 157–163.

Tolasa, S., Cakli, S., Kisla, D., & Dincer, T. (2012). Quality and shelf-life assessment of pasteurized trout soup during refrigerated storage. *Journal of Aquatic Food Product Technology, 21*, 321–329.

Wuytack, E., Soons, J., & Michiels, C., (1997). Rapid measurement of pressure-induced germination of Bacillus subtilis spores expressing green fluorescenct protein. High Pressure Research in the Biosciences and Biotechnology, p- 261–264 (ed.) K. Heremans, Leuven University Press.

Xie Q., Xu B., Xu Y., Yao Z., Zhu B., Li X., & Sun Y. (2022). Effects of different thermal treatment temperatures on volatile flavour compounds of water-boiled salted duck after packaging. *LWT*, *154*, 112625.

Yi, J., Kebede, B. T., Grauwet, T., Loey, A. V., Hu, X., & Hendrickx, M. (2016). Comparing the impact of high-pressure processing and thermal processing on quality of "hayward" and "jintao" kiwifruit purée: Untargeted headspace fingerprinting and targeted approaches. *Food and Bioprocess Technology, 9*, 2059–2069. https://doi.org/10.1007/s11947-016-1783-1

Yi, J., Kebede, B. T., Dang, D. N. H., Buvé, C., Grauwet, T., Van Loey, A., Hu, X., & Hendrickx, M. (2017). Quality change during high pressure processing and thermal processing of cloudy apple juice. *LWT – Food Science and Technology*, *75*, 85–92.