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Energy and quality performance assessment of emerging and conventional food preservation technologies

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Abstract

The energy performance of emerging food pasteurisation technologies (high pressure processing, microwave volumetric heating, ohmic heating) are evaluated to establish whether they can offer significant reductions in energy consumption and overall carbon emissions, relative to conventional processes, while delivering equivalent microbiological lethality, nutritional and organoleptic quality under commercially-representative processing conditions. Product quality (vitamin C and flavour compounds) data have been collected using established analytical and instrumental methods to benchmark achievable product quality improvements. The results show that for maintaining the raw product quality, the emerging electro-technologies are more energy- and primary resource-efficient, subject to identified operating parameters.

Keywords: Food pasteurisation; Energy demand; High pressure processing; Microwave heating; Ohmic heating

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1. Introduction

A range of electricity-driven food preservation technologies is becoming commercially available to the food industry and there is significant interest in their potentials to yield premium-quality products [1, 2, 3, 4]. Among them are processes such as high pressure (HPP), pulsed electric field (PEF), pulsed light, ultrasonic processing, and volumetric heating schemes such as microwave (MVH), radiofrequency (RF) and ohmic (OH) heating. Industrial implementation is relatively low due to a combination of factors including risk aversion, higher capital investment costs, and in some cases, lower production rates compared to conventional technologies. The food and beverage market is extremely competitive. Therefore, in addition to product quality improvements, it is important to reduce operating costs and environmental impacts which are the subject of the current contribution. In this work, we measure and compare the energy performance of HPP, microwave volumetric heating MVH, ohmic heating OH and conventional thermal treatment UHT, for the delivery of equivalent microbiological lethality in orange juice, under commercially-representative processing conditions. We also collect and compare corresponding product quality data (vitamin C and flavour compounds) using established analytical methods to benchmark achievable product quality improvements. The energy data is translated to carbon emissions using appropriate UK emission factors to evaluate sustainability.

2. Materials and methods

A series of trials were conducted using continuous flow microwave processing, conventional heat treatment, high pressure processing and ohmic heating. For the first three processes, trials were conducted using orange juice produced at Campden BRI. Fresh oranges of good and uniform quality (total mass, 300 kg) were purchased from a local supplier and delivered in 15 kg boxes the day before processing. On delivery they were transferred into open crates and chill-stored at 5°C (Fig. 1). The oranges were washed with water and juice was extracted using an FMC citrus reamer (which was designed to mimic industrial extraction practices). Juice was collected in 10 L stainless steel buckets, immediately wrapped in cling-film and covered in black bags (Fig. 2). For the ohmic heating process, fresh oranges were purchased from another supplier, the juices extracted using a compact juicer (Philips HR1832/01) and processed immediately at Brunel University London. For microwave processing, a Dynowave – AMT 4 continuous-flow system (Advanced Microwave Technologies, Scotland), with nominal flowrate 115 ± 5 L/h, and a four-magnetron power source was used for a target process of 75 °C for 26 s. For the ohmic process, a PID temperature-controlled, 10 kW batch ohmic heater (CTech Innovation, Capenhurst, Chester, UK) operating at atmospheric pressure was used. The heating cell had electrode dimensions 90 mm wide x 95 mm, with an electrode spacing of 80 mm, and fed with 250 ml orange juice, heated from ambient to 76°C, with a holding time of 26s, similar to the microwave system. For the HPP, a 700 ml laboratory-scale system (EPSI, Belgium), but with only 36% capacity utilisation (also known as fill-ratio) for juice processing, was used. The pressure medium consisted of water with 3% (v/v) of MKU, an oil based corrosion inhibitor, and the operating conditions were, holding pressure: 600 MPa, compression time, ~1 min, holding time, 3 min and maximum temperature, 32°C. To enable the conventional process energy to be logged using the same measuring principle as the electrically-driven emerging technologies, the conventional technology is represented here by an electrically-powered hot water-to-orange juice heat exchanger. This is an FT74XTS miniature-scale UHT/HTST processing system (Armfield, UK). The target process was set at 76.8 °C for 15s. Fig. 1 (a-d) shows a schematic of each process. For the MVH process, orange juice OJ_in, at the inlet, flows through the heating section, within the microwave chamber MC, then through a holding stage for the required hold time, before being cooled via cooling water CW, to yield the pasteurised, cooled orange juice product OJ_out. MCW is the magnetron cooling water, while in, and out represent inlet and outlet values, respectively. The same principle is used for the UHT process, except that the heating is provided by an indirect electrical resistance heating element EH, which heats up cold process water PW, which subsequently exchanges heat with the orange juice. In each case, energy demand as measured in situ, while the products were sent for quality (flavour compound and vitamin C) analysis using instrumental/analytical methods. Experiments were performed in triplicates.

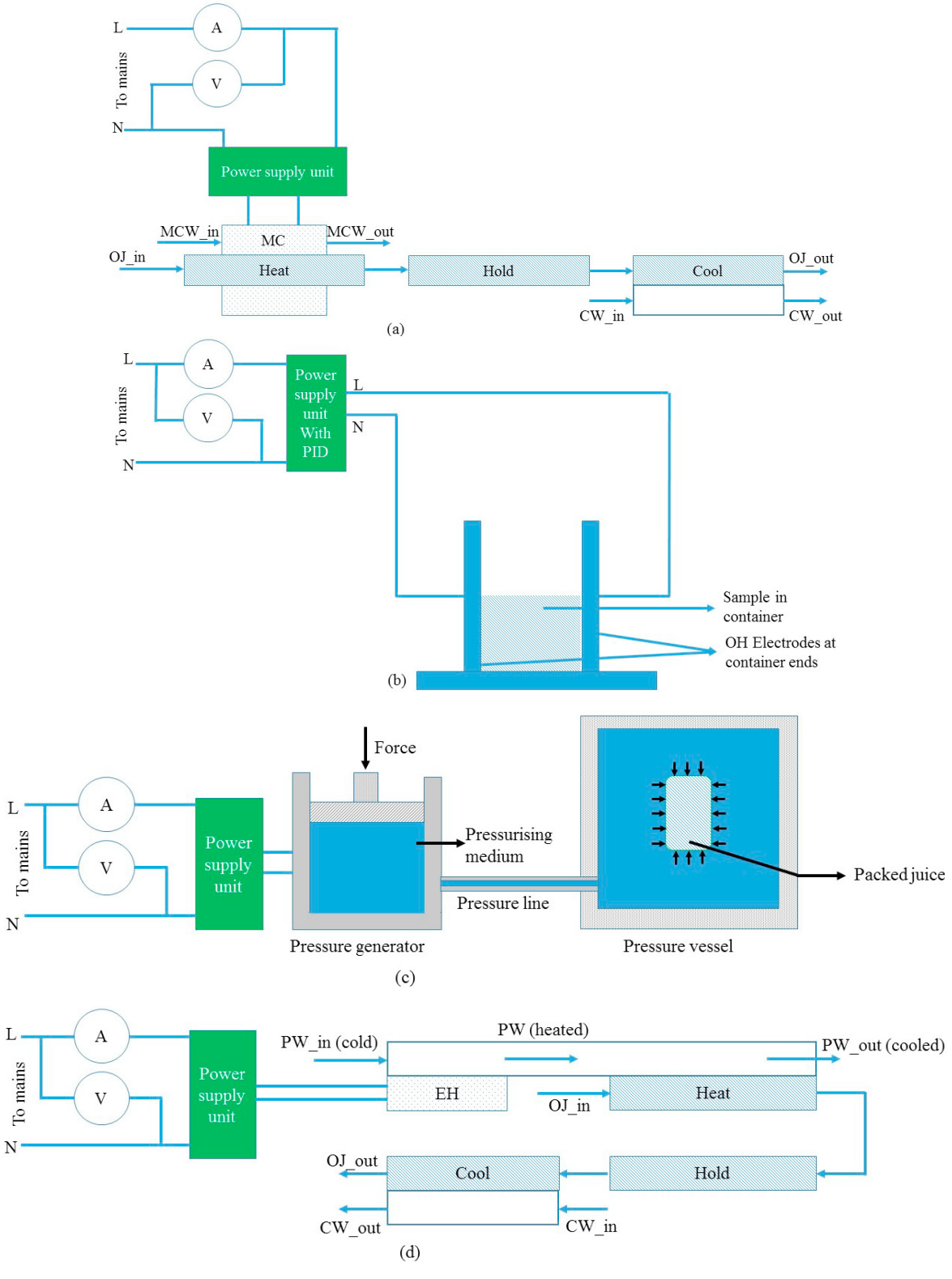

Fig. 1. (a) MVH; (b) OH; (c) HPP; (d) UHT systems.

2.1. Energy measurements and corresponding carbon emission estimations

Electrical energy data for the HPP, MVH and UHT/HTST systems was recorded using a Fluke 1730 energy logger. As each system was three-phase power supply-driven, the logger monitored each phase voltage (by connecting the meter voltage coil V terminals between each live phase conductor L, and the neutral N from the mains). Respective line currents were measured using the induction measuring principle (clamping the jaws A of the meter over each live phase conductor). For the OH process, driven by a single-phase supply, phase voltage, current, power factor, power and cumulative energy were each logged using a Fluke 345 energy logger. The per-phase voltage and current coil connections for all electrical energy measurements are illustrated in Fig. 1 a- d. Thermal energy delivery to the food (for the MVH, OH and UHT processes) was determined from temperature measurements, mass measurements for batch processes, flowrate measurements for continuous processes and thermo-physical data (density and specific heat capacity) from the literature. For the non-thermal process (HPP), an equivalent thermal energy is expressed as the thermal energy consumed by the conventional (UHT) process in heating the HPP product from room temperature (25 °C) to the UHT target temperature [4]. In each case, the energy efficiencies were obtained as the ratio of this thermal energy to the electrical energy consumption as obtained by measurements. Specific energy (energy consumption per litre of product) was estimated as the ratio of the electrical energy consumed to the product volume (for the batch processes), and the ratio of the instantaneous power to the instantaneous product flowrate (for continuous processes). Greenhouse gas emissions corresponding to energies consumed in each case, were estimated using UK emission factor data [5, 6]. The emissions data are collected for electricity (for the electricity-driven emerging technologies) and natural gas (for conventional thermal treatment) at boiler efficiency lower and upper limits of 50% and 80% [7, 8]. Using functional units of 1.0 kWh of thermal energy delivery to the juice, and 1.0 L of juice, the emissions in kgCO2e/kWh and kgCO2e/L, respectively, were computed for each technology. Details of the method are available in [4].

2.2. Quality measurements

The quality tests (flavour compound and vitamin C analyses) were conducted in two phases: the MVH, HPP and UHT processes were analysed first, then, after a significant time lag, the OH-processed juice samples (from a different set of raw materials), were also analysed together with raw samples. During this time lag, instrumental conditions changed, but comparisons between all the results were based on normalised values as will be discussed later.

For flavour compound analysis, orange juice samples, treated using the different procedures were compared to see how the procedures could have affected their volatile profiles. The samples were analysed using solid phase micro-extraction and gas chromatography / mass spectrometry (GC/MS). For each sample, an appropriate amount of product was placed into a 20ml vial, which was then sealed. The vial was equilibrated at 75°C for 5 mins with agitation. The headspace of the vial was then sampled for 5 mins at 75°C (with agitation) using a carboxen/polydimethylsiloxane/di-vinyl-benzene-coated SPME fibre. The volatiles adsorbed onto the fibre were analysed by thermal desorption at 270°C in the injector port of a GC/MS. Analyses were carried out on an Agilent 7890A gas chromatograph (GC) and Agilent 7200 accurate mass Q-TOF mass spectrometer (MS) via a CTC Combi-Pal auto-sampler.

Total vitamin C concentration (made up of L-ascorbic acid (AA) plus dehydro-1-ascorbic acid, DHAA) was determined using high-performance liquid chromatography (HPLC). After extraction, AA was oxidized enzymatically to DHAA with the aid of ascorbate oxidase. The latter compound was condensed with ophenylenediamine (OPDA) to its highly fluorescent quinoxaline derivative. This derivative was separated on a reversed-phase HPLC column and detected fluorometrically. Total vitamin C can be determined in concentrations as low as 0.2 pg/g.

3. Results and discussion

3.1. Energy and emission results

Fig. 2 (a-d) show the energy density (specific energy) and efficiency results for all the studied technologies. It is observed that ohmic heating is the most-efficient, attaining an overall efficiency of 80%, followed by the microwave system (with magnetron cooling electrical energy, discounted), which has an efficiency of 54%. Ordinarily, the

microwave system has an efficiency of 45%, similar to the electrically-driven UHT system (46%). The HPP system at only 36% capacity utilization (fill ratio), has the least efficiency (31%). This efficiency, an equivalent thermal efficiency, is obtained as the ratio of the thermal energy required to raise 1 L of the juice from 25°C to 76°C (as required by the conventional UHT), to the cumulative electrical energy (~645 kJ, Fig. 2c, right) consumed by the HPP system. Corresponding GHG emissions as shown in Tables 1 & 2, follow the same trend. Due to the increasing UK electricity grid decarbonisation per-year, the electricity-driven emerging technologies are becoming more GHG-efficient. The conventional system has a poor start-up performance (due to heat transfer rate limitations), as seen in the long transient time (Fig. 2d) over which 12.72 MJ of energy is lost. The HPP, MVH and OH processes do not have this problem as electric switching has an almost instantaneous effect on thermal energy generation.

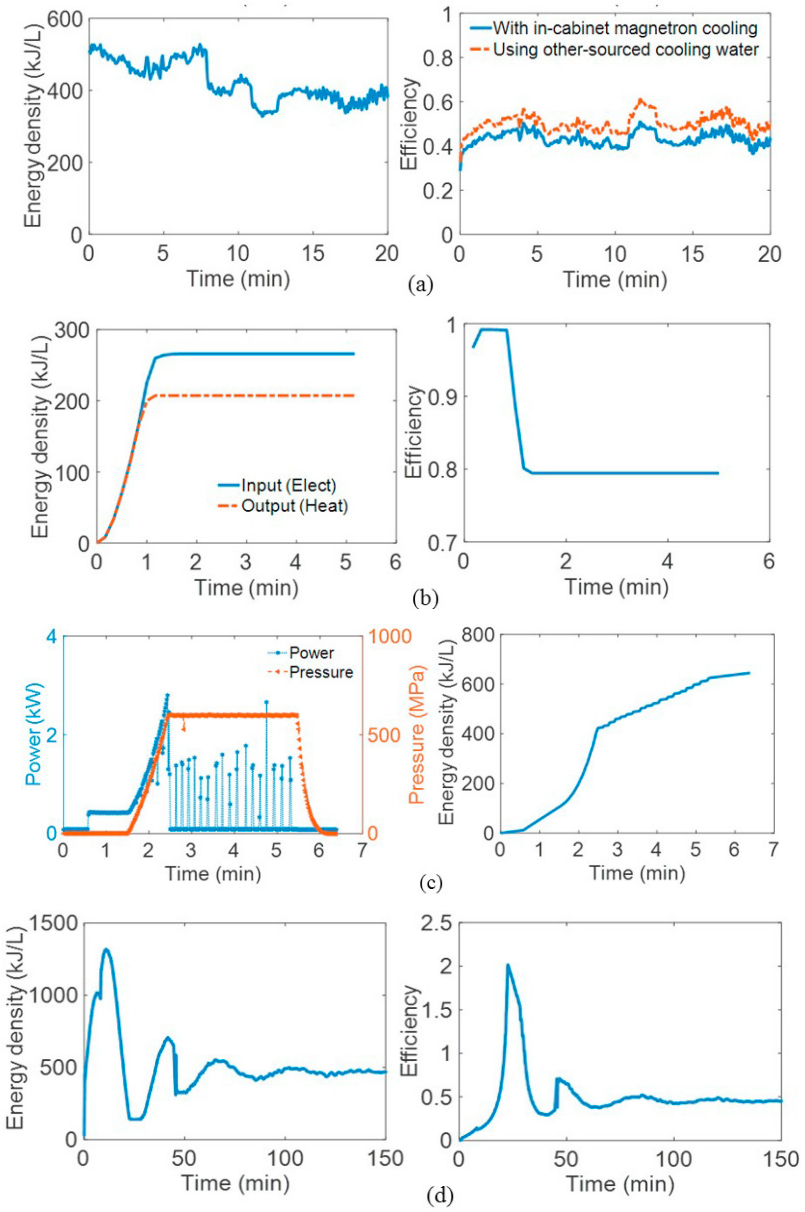

Fig. 2. (a) MVH; (b) OH; (c) HPP; (d) UHT energy performance results. HPP system shows pressure plots since as a non-thermal process, pressure and not temperature, is primarily responsible for process lethality. For the same reason, energy (thermal) efficiency does not apply

Table 1. Pasteurisation process GHG emissions (gCO_2e/kWh of heat delivery) across technologies (2016 – 2020).

Year	MVH	OH	HPP	UHT(E)	UHT(G50)	UHT(G80)
2016	488.9	275.0	709.7	478.3	635.0	400.3
2017	473.3	266.2	687.1	463.0	635.0	400.3
2018	455.6	256.3	661.3	445.7	635.0	400.3
2019	433.3	243.8	629.0	423.9	635.0	400.3
2020	402.2	226.3	583.9	393.5	635.0	400.3

Table 2. Pasteurisation process GHG emissions (gCO_2e/L of orange juice) across technologies (2016 – 2020).

Year	MVH	OH	HPP	UHT(E)	UHT(G50)	UHT(G80)
2016	23.2	12.7	39.4	28.7	38.2	24.1
2017	22.5	12.3	38.2	27.8	38.2	24.1
2018	21.7	11.9	36.8	26.8	38.2	24.1
2019	20.6	11.3	35.0	25.5	38.2	24.1
2020	19.1	10.5	32.5	23.6	38.2	24.1

3.2. Quality (flavour compound and vitamin C) analysis results

For the first phase of the experiments (comparing the MVH, HPP, UHT and HPP-control samples HPC), the GC/MS chromatograms from the samples (Fig. 3 a-d), appeared to be visually similar. The chromatograms were therefore subjected to chromatographic deconvolution using software provided with the instrument, to measure the volatile peaks present in the samples. Over one hundred potential peaks were measured in this way. The areas of the peaks of those components in the different samples that differed most significantly between treatments are shown in Fig. 4a, expressed graphically as data normalised against the largest peak of each of the peak types. It is important to note that none of these components were significantly different ($p<0.05$) from the other. GC/MS analysis of the different orange juice samples demonstrated very little difference between the samples based on the treatments to which they had been subjected. It was possible to distinguish the control HPP and test HPP samples from each other and from the other samples but only using PCA analysis with a confidence level of 0.8; hence it is questionable whether the differences used to make these distinctions should be considered of any practical significance. It was not possible to distinguish the microwave and UHT-treated samples from each other. For the second phase of the experiments (comparing the OH and raw control samples), the chromatograms from the samples (not shown), were also visually similar. The chromatograms were therefore subjected to chromatographic deconvolution, to measure the volatile peaks present in the samples. The areas of the peaks of those components in the different samples that differed most significantly between treatments are shown in Fig. 4b, expressed graphically as data normalised against the largest peak of each of the peak types. None of these components were significantly different ($p<0.05$) from the other. It was possible to distinguish the OH from the raw samples by their slightly higher levels of terpenoid and sesquiterpenoid compounds, but only using PCA analysis with a confidence level of 0.8; hence it is questionable whether the differences used to make this distinctions should be considered of practical significance. The results obtained from the OH-treated and control raw orange juice were then compared with those obtained for the MVH, HPP, UHT and HPP-control samples. Due to the significant time difference between the analyses, changes in the instrumental conditions limit the direct comparison of the raw peak areas, especially as the raw materials for both cases were obtained from different sources. However, the relative levels of the peaks between samples analysed at the same time can be suitably compared. The peaks demonstrating the greatest potential difference between the OH and raw samples were all identified as terpenes or sesquiterpenes. All the peaks found to be demonstrating greatest potential difference between the MVH, HPP, UHT and HPP-control samples were also identified as terpenes or sesquiterpenes, except for two peaks, one of which was identified as hexyl acetate, and the other as an alkyl compound.

The two non-terpenoid peaks were not of a sufficient size to be quantified in the OH and raw samples, and as such, only the relative levels of the selected terpenoid peaks were considered. Comparison of the relative levels of the selected peaks indicate that relative to the control samples in each set, the OH and HPP processed samples did not show a reduced level of any of the peaks; yet, the microwave processed samples exhibit slightly reduced levels of seven of the eleven peaks, while the UHT processed samples exhibit slightly reduced levels of four of the eleven peaks. It should be noted however, that as previously discussed, none of the peaks were found to possess a corrected p-value of less than 0.05, indicating that none of the peaks appear likely to exhibit statistically significant differences between the samples from each set of analyses. As such, any comparison of the relative levels between the samples could be considered not to be statistically significant. For vitamin C determination in the MVH, HPP, UHT and HPP-control, HPC samples, it is observed (Fig. 5a), that the variation in vitamin C levels within each process was much greater than the variation between processing types which was not statistically significant ($p>0.05$). For similar measurements with a differently-sourced orange raw material and at a later date (OH-treated and raw juice samples), the results (Fig. 5b) also show no significant difference between the samples in terms of vitamin C concentration. Overall from Fig 5 a and b, no significant vitamin C degradation between the control/raw and all the processed samples is observed. The emerging process electro-technologies therefore compete favourably with fresh products, in this regard.

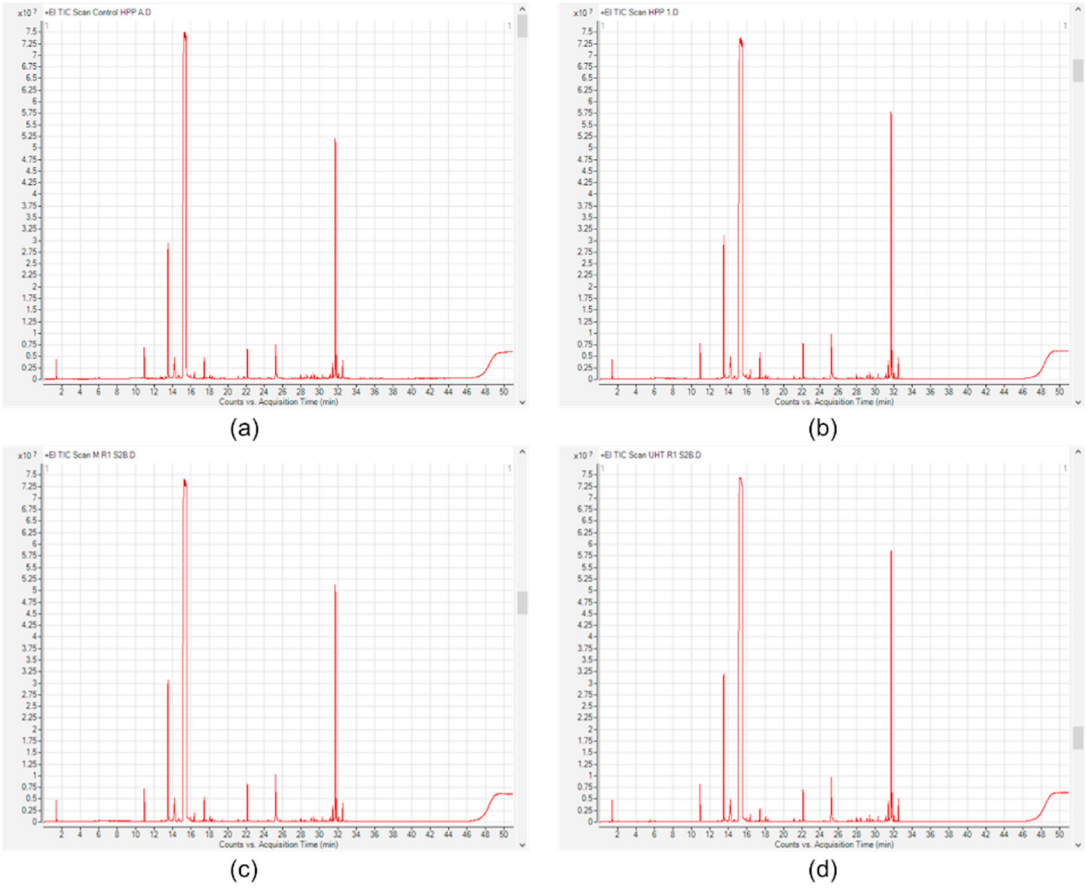

Fig. 3. GC/MS Chromatograms of (a) MVH (b) HPP (c) UHT and (d) HPP control (HPC) processed juice

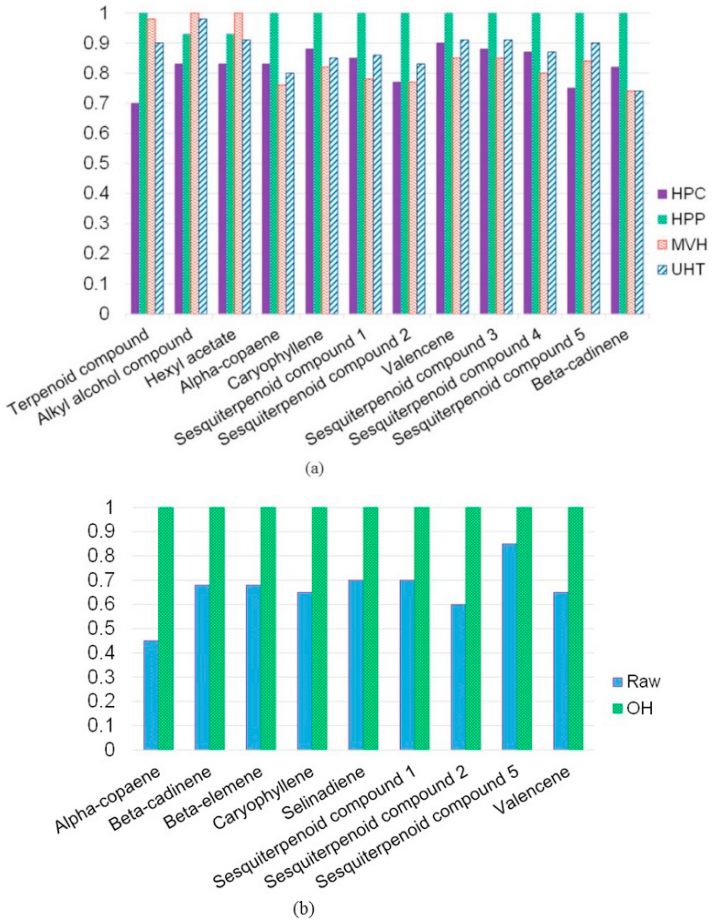

Fig. 4. (a) MVH, UHT, HPP and HPP control (HPC); (b) OH and raw control flavour compound analysis results.

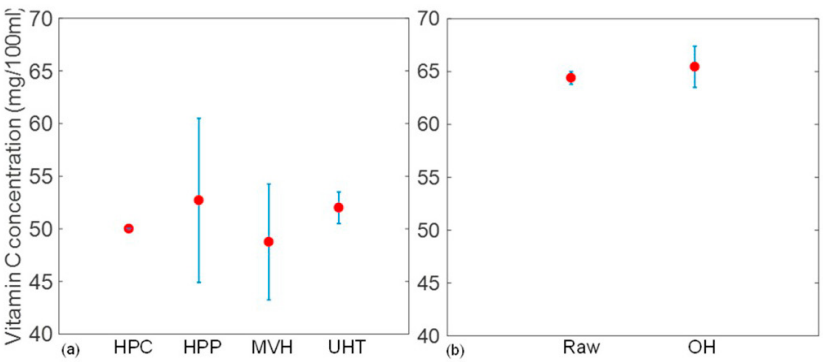

Fig. 5. (a) MVH, UHT, HPP and HPP control (HPC); (b) OH and raw control vitamin C analysis results.

4. Conclusion

The results of this study indicate that electricity-driven emerging pasteurisation technologies are promising alternatives to conventional processes, with respect to energy consumption and overall carbon emissions, while

delivering high-quality under commercially-representative processing conditions. Under these conditions, no significant differences are observed in the vitamin C content and flavour compounds across the technologies.

Although the primary energy efficiency of the studied high pressure processing and microwave systems may be lower than that of state-of-the-art gas-fired thermal technologies, ohmic heating by virtue of its much higher electrical efficiency, may provide a better outcome if the efficiency of local electricity generation is reasonably high. A significant advantage of the emerging technologies is the reduction in GHG emissions (UK) required for the same pasteurising effect, owing to the increasing decarbonisation of the UK electricity grid. If this trend continues as expected, these advantages are anticipated to increase appreciably with time.

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