


# High-pressure processing, microwave, ohmic, and conventional thermal pasteurization: Quality aspects and energy economics

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## Funding information

Research Councils UK, Grant/Award Number: EP/K011820/1

## Abstract

In this work, we collect and compare product quality data (vitamin C and flavor compounds) for orange juice processed using conventional thermal and innovative (high pressure, microwave, and ohmic) technologies under commercially representative conditions. We also measure and compare their respective energy demands and associated costs. While significant efficiency gains are made due to electrification using the innovative technologies (especially the ohmic process), the high per-unit costs of grid electricity results in poorer processing economics relative to conventional gas-fired technologies. UK levelized cost of electricity (LCOE) data suggest that as the share of renewables in the electricity generation energy mix is increased, the innovative technologies will eventually become more economical, in addition to the significant greenhouse gas emission reductions per liter of product. No significant differences are observed in the quality attributes of the processed product across all the technologies. The innovative electricity-driven technologies are thus promising alternatives to conventional thermal pasteurization.

## Practical applications

Beverage processing by conventional thermal treatment is energy consuming and can adversely affect the sensory and nutritional quality attributes of the final product. Innovative, mild processing techniques such as high-pressure processing, microwave, and ohmic heating are increasingly gaining industry attention due to their potentials to significantly address these challenges. Actual uptake is still relatively low due to factors including risk aversion, process validation issues, and economics. This work compares these technologies with conventional thermal treatment in terms of critical product quality attributes (vitamin C and flavor compounds) and process energy economics under commercially representative processing conditions. The results of this study will be useful as a guide to food processors for implementing the innovative technologies and could lead to new product development and process optimization.

## 1 | INTRODUCTION

On the average, 1 billion liters of fruit juice is consumed per year in the UK alone (British Soft Drinks Association, 2017), a significant

proportion of which is pasteurized. Higher figures are reported for beer over 4 billion in the UK, 24 billion in the US, and a little less in the EU (Kirin, 2017). Given the high kJ of energy required to pasteurize 1 L of typical beverages using conventional thermal techniques,

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pasteurization forms a significant proportion of the low-temperature heat energy service demands of the beverage industry. Hence, although microbial safety and good nutritional and organoleptic quality are of primary interest, it is important to also develop more sustainable pasteurization processes. A range of electricity-driven innovative processing technologies such as high pressure (HPP), microwave (MVH), radio-frequency (RF), ohmic (OH), pulsed electric field (PEF), pulsed light, ultrasonic processing among others, is becoming commercially available to the food industry. There is significant interest not only in their capacity to produce superior quality products but also in their energy saving potentials. Actual uptake is still relatively low due to factors including risk aversion, process validation issues, and economics. However, to sustainably meet the ever-increasing food intake needs of the growing population of the world at premium quality levels, a shift from conventional thermal to innovative preservation techniques is imperative (Langelaan et al., 2013; Probst, Frideres, Pedersen, & Amato, 2015). For processes already validated for microbial safety, it is therefore important to analyze comparatively in one-step, their impacts on nutritional and sensorial aspects of quality, as well as energy-efficiency and associated economics.

Recent research efforts on the application of innovative technologies in beverage processing have focused on different critical aspects, each, often considered in isolation. Among these are pathogenic microorganism and enzyme inactivation kinetics (e.g., Brugos, Gut, & Tadini, 2018; Milani, Alkhafaji, & Silva, 2015; Saxena, Makroo, Bhattacharya, & Srivastava, 2018; Siguemoto, Funcia, Pires, & Gut, 2018), structural and functional parameters (Bogahawaththa, Buckow, Chandrapala, & Vasiljevic, 2018; Li, Ye, Tian, Pan, & Wang, 2018), and sensory and nutritional quality attributes (Deng et al., 2018; Evrendilek, Celik, Agcam, & Akyildiz, 2017; Makroo, Rastogi, & Srivastava, 2017; Nayak, Chandrasekar, & Kesavan, 2018). Comprehensive reviews of previous work in these areas include Ortega-Rivas and Salmeron-Ochoa (2014), Gabrić et al. (2018), Jiménez-Sánchez, Lozano-Sánchez, Segura-Carretero, and Fernández-Gutiérrez (2017), Barba, Koubaa, Prado-Silva, Orlie, and de Souza Sant'Ana (2017), and Bevilacqua et al. (2018) studies. Other studies have focused primarily on energy and sustainability issues (Aganovic et al., 2017; Atuonwu et al., 2018; Atuonwu & Tassou, 2018a, 2018b; Rodriguez-Gonzalez, Buckow, Koutchama, & Balasubramanian, 2015). Atuonwu et al. (2018) compared the energy consumption per liter of orange juice by microwave, ohmic, HPP, and conventional thermal processes as well as the associated greenhouse gas (GHG) emissions. Studies simultaneously considering energy, energy economics, nutritional, and sensory quality aspects have been rare. The purpose of this work, therefore, is to evaluate and compare the impacts of some of the innovative processing techniques (HPP, MVH, and OH), on final product quality attributes and the energy economics of processing, under commercially representative processing conditions. Vitamin C concentration is taken as an indicator of nutritional quality, and flavor volatiles, for sensory quality. Specific energy consumption figures for electricity and fuel (gas)-driven technologies are used in conjunction with corresponding average UK energy pricing data to evaluate energy economics over time. UK levelized cost of electricity (LCOE) data are used to project into the future economic

prospects (in terms of pasteurization energy costs) of using the innovative electricity-driven technologies. HPP, MVH, and OH systems are among the most mature of the emerging food preservation technologies with a significant number of commercial, industrial-scale installations worldwide. A recent survey conducted in Europe and North America (Jermann, Koutchma, Margas, Leadley, & Ros-Polski, 2015) identified HPP and MVH as the two leading emerging food-processing technologies of greatest commercial interest, while OH is perfectly suited for the fast, volumetric heating of moderately conductive fluids such as orange juice. Hence, in this work, these technologies are compared with conventional thermal treatment with respect to product quality and energy performance, simultaneously.

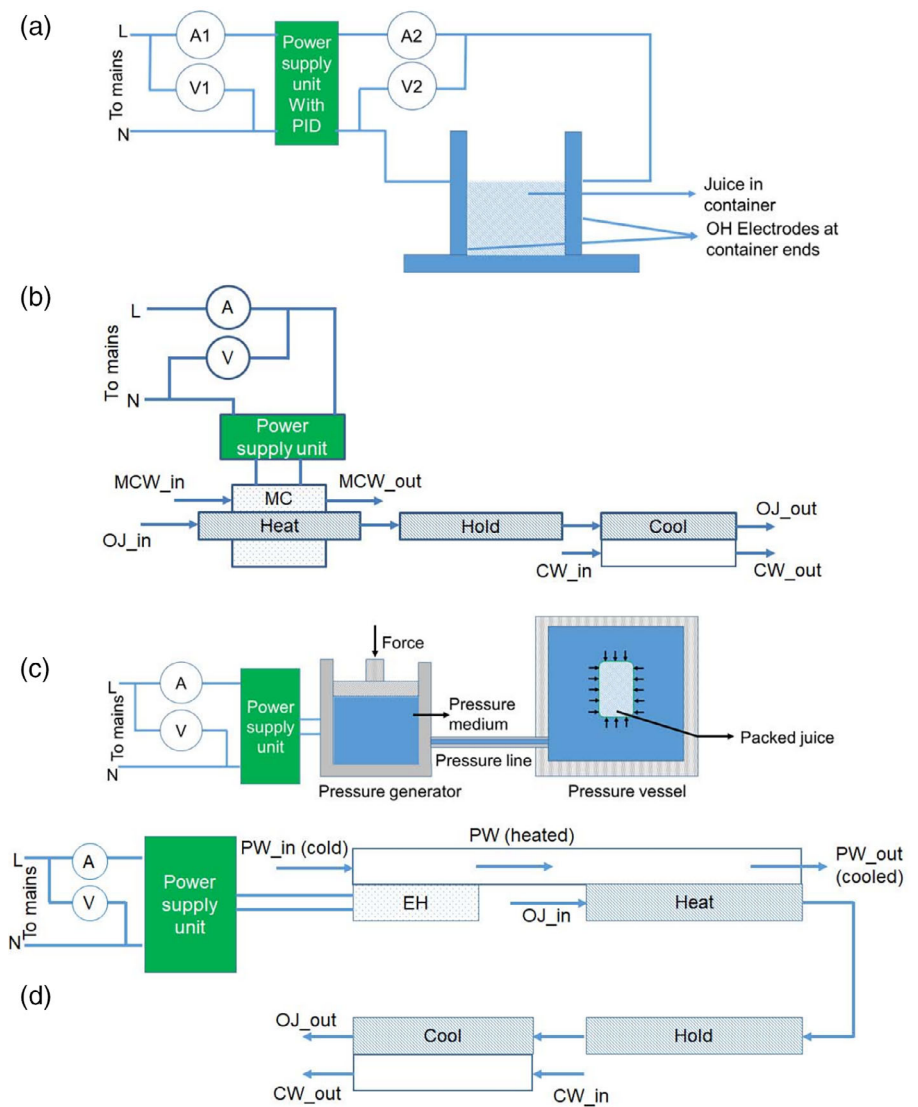
## 2 | MATERIALS AND METHODS

### 2.1 | Material preparation, processing, and energy measurements

Trials were conducted using a continuous flow microwave (MVH) system, an indirect electrical resistance-heated system (CTT, representing conventional thermal treatment), and batch high-pressure processing (HPP) and ohmic heating (OH) systems. The OH system of Figure 1a (a 10-kW batch system, CTech Innovation, Capenhurst, Chester, UK) consists essentially of a polypropylene product container (with an electrode at each end), into which the juice was filled, and a free-standing power control panel connected to it. About 250 ml of orange juice was fed into the product container for processing. The polypropylene product container internally measures 90 mm wide × 95 mm high, with a variable length between 80 and 300 mm, adjustable between the two-end electrode housings via 80 mm- and 220 mm-long spacer sections, fitted with tie rods. The maximum operating voltage between the electrodes is the mains supply voltage (~240 V, 50 Hz). This electrode voltage is controllable via the PID controller between 0 and maximum voltage to achieve desired product temperatures. In this work, only the 80 mm option, corresponding to a maximum voltage gradient of ~30 V/cm, is used. In the MVH system of Figure 1b (a 12-kW capacity Dynowave—AMT 4 system, courtesy Advanced Microwave Technologies, Scotland), orange juice OJ flowed through the microwave chamber MC, then through a holding tube, before being cooled via heat exchange with cold water CW. MCW is the magnetron (microwave generator) cooling water. The system has 4 magnetrons as power sources, each supplying 3 kW, and has a cylindrical cavity of diameter 34 mm, and length 550 mm.

In the HPP system of Figure 1c, a 700-ml laboratory-scale HPP system (EPSI, Belgium), a pressure medium (water with 3% [v/v] of MKU, an oil-based corrosion inhibitor) is pumped via an intensifier pump to an already-filled pressure vessel containing the packaged juice (about 250 ml). The pressure was recorded using an MMS3000 data logger (RiL Instruments, Nottingham), logging at 1 s intervals. Figure 1c shows the operating principle of the HPP system, leading to pressure build-up to a maximum of 600 MPa, which is maintained for a hold time of 3 min, after which, rapid depressurization occurs. The juice temperature during the hold step is  $30 \pm 2^\circ\text{C}$  and reduces to 12

**FIGURE 1** Schematics of (a) ohmic heating system, (b) microwave heating system, (c) high-pressure processing system, and (d) conventional thermal treatment system



$\pm 1^\circ\text{C}$  after depressurization. In the CTT system of Figure 1d (an FT74XTS miniature-scale high-temperature short-time processing system, Armfield, UK), process water (PW) was heated by an electrical indirect resistance heater (EH). The resulting hot water exchanged heat with flowing cold orange juice OJ. When the target temperature was reached, the OJ flowed through the holding tube for the desired residence time before subsequent cooling. Further details of each processing equipment are available in Atuonwu et al. (2018). In all the processes, electrical power and energy consumption were measured using Fluke energy meters. Figure 1 shows schematics of each processing scheme with the energy instrumentation connections. In each case, the current coil A of the meter is in series with the phase-to-neutral circuit. This is achieved by clamping the jaws of the meter around the live phase conductor L from the mains. The voltage coil V is connected in parallel (i.e., one terminal to the live phase conductor L and the other to the neutral N). Overall, the instantaneous power  $P(t)$  is measured and then integrated with respect to time to yield the cumulative energy consumption.

For the MVH, CTT, and HPP processes, trials were conducted using orange juice produced at Campden BRI. Fresh oranges of good and uniform quality were purchased from a local supplier (Drinkwater, Chipping Campden), transferred into open crates and chill-stored at  $5^\circ\text{C}$ . The oranges were washed with water and juice, extracted using an FMC citrus reamer. The juice was collected in 10 L stainless steel buckets, immediately wrapped in cling-film and covered in black bags (to prevent vitamin C degradation) before processing. Processing conditions were  $75^\circ\text{C}$ , 26 s for the MVH process,  $76.8^\circ\text{C}$ , 15 s for the CTT process, and 600 MPa, 3 min for the HPP. A control sample was obtained by processing some orange juice industrially in a Hiperbaric 135 HPP unit of 135 L capacity at 600 MPa with a hold time of 4 min, 20 sec. For this purpose, clear, plastic, square PET Bottles (Patrico Ltd., Industrial Container Stockists) were hand-filled with 250 ml juice and transported, chilled, to a contract HPP packer. The transit time was approximately 90 min. For each of the MVH, CTT, and HPP, 12 samples were collected in total, plus the control; six of them were analyzed for vitamin C retention and the other six for volatile flavor compounds. The samples were all collected in a clean environment.

After a significant time lag, further experiments were conducted using ohmic heating OH. For the OH process, fresh oranges were purchased from another supplier, the juices extracted using a compact juicer (Philips HR1832/01) and processed immediately (75°C, 26 s) at Brunel University London. Fast cooling was achieved by quickly transferring the juice to an aluminium pan immersed in ice/liquid water mixture (ice obtained from freezer at -20°C) and stirred vigorously. All experiments were performed in triplicate and raw orange juice used as control. To minimize vitamin C degradation, the samples for vitamin C analysis were fed into cans with no headspace, covered in black sacks (to minimize exposure to light), and frozen, before transporting to the analytical facilities, covered in ice-filled ThermoFreeze sheets.

All the thermal processes had temperature-time trajectories (Atuonwu et al., 2018), equivalent to 70°C for 2 min based on the death time Equation (1) for a z-value of 7.5°C. Heating at 70°C for 2 min has been used in previous work (Pao & Davis, 1999) to achieve a 5-log *Escherichia coli* population reduction in orange media. The HPP processing condition deployed is commonly used commercially and found to achieve similar effects (Daher, Le Gourrierc, & Perez-Lamela, 2017). Pathogenic *E. coli* may survive in acid environments such as fruit juices for long periods (Patil, Bourke, Frias, Tiwari, & Cullen, 2009), and has been implicated in many outbreaks of foodborne illnesses from fruit juices (CDC, 1996). Regulators, for example, the US National Advisory Committee on Microbiological Criteria for Foods have recommended that production of fruit juices should include treatments capable of producing a cumulative 5-log-unit reduction in the levels of *E. coli* (USDA, 1997). It is therefore important to investigate the energy economics and quality aspects of various equivalent processing methods with respect to this microorganism.

$$F = \int_0^t 10^{\frac{T(t)-T_{ref}}{z}} dt \quad (1)$$

## 2.2 | Head space volatile analysis for flavor compounds

Samples of orange juice processed using the different technologies were analyzed by solid phase micro-extraction SPME and gas chromatography/mass spectrometry GC/MS (Grauwet & Shpigelman, 2018). For each sample, an appropriate amount of product was placed into a 20-ml vial, which was then sealed. The vial was equilibrated at 75°C for 5 min with agitation. The headspace of the vial was then sampled for 5 min at 75°C (with agitation) using a carboxen/polydimethylsiloxane/divinylbenzene-coated SPME fiber. The volatiles adsorbed onto the fiber were analyzed by thermal desorption at 270°C in the injector port of the GC/MS equipment. Analyses were performed on an Agilent 7890A gas chromatograph (GC) and Agilent 7200 accurate mass Q-TOF mass spectrometer (MS) via a CTC Combi-Pal auto-sampler. The GC/MS conditions

were as follows: Column: 30 m × 0.25 mm fused silica with VF-5MS stationary phase; helium carrier gas flow rate: 1 ml/min; desorption temperature: 270°C; column temperature 40°C for 5 min; then 4°C/min to 200°C; then 30°C/min to 350°C; then hold for 3 min. MS analysis mode: SCAN (33–350 *m/z*). Peaks were tentatively identified by spectral matching with the NIST library of mass spectra data. The results obtained were subjected to statistical analysis using one-way ANOVA (for more than two parameters), moderated *t*-test (for two parameters), asymptomatic *p* value computations and the Benjamini-Hochberg Multiple Testing Correction method.

## 2.3 | Total vitamin C analysis

A high-performance liquid chromatographic (HPLC) method was used to determine the total vitamin C which is made up of L-ascorbic acid (AA) plus dehydro-1-ascorbic acid (DHAA; Speek, Schriver, & Schreurs, 1984). After extraction, the AA was oxidized enzymatically to DHAA with the aid of ascorbate oxidase (AO). The latter compound was condensed with ophenylenediamine (OPDA) to its highly fluorescent quinoxaline derivative, which was then separated on a reversed-phase HPLC column and detected fluorometrically.

## 2.4 | Energy cost estimations

To determine the pasteurization energy costs per liter of product, the specific energy SPE (energy per liter) is first determined for each process.

For the continuous processes, the instantaneous specific energy is,

$$SPE_c(t) = \frac{\int_0^t P(t) dt}{\int_0^t Q(t) dt} \quad (2)$$

where  $P(t)$  is the instantaneous power consumption and  $Q(t)$  is the instantaneous volumetric flowrate of the process.

For the batch processes, with hold-up volume  $V$ , the instantaneous specific energy is

$$SPE_b(t) = \frac{1}{V} \int_0^t P(t) dt \quad (3)$$

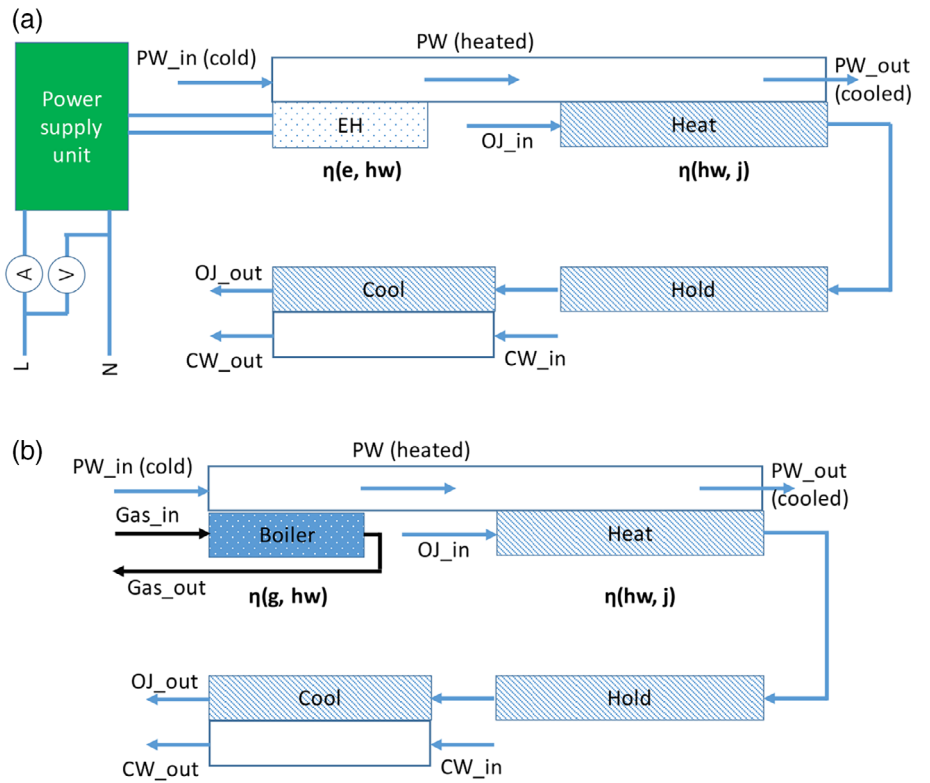
$SPE(t_f)$  is the overall specific energy consumption where  $t_f$  is steady-state time (or greater) for the continuous processes and the holding time for the batch processes.

If  $cpu_e$  is the electrical energy cost per unit, the energy cost for pasteurizing 1 L of juice using the electricity-driven technologies is

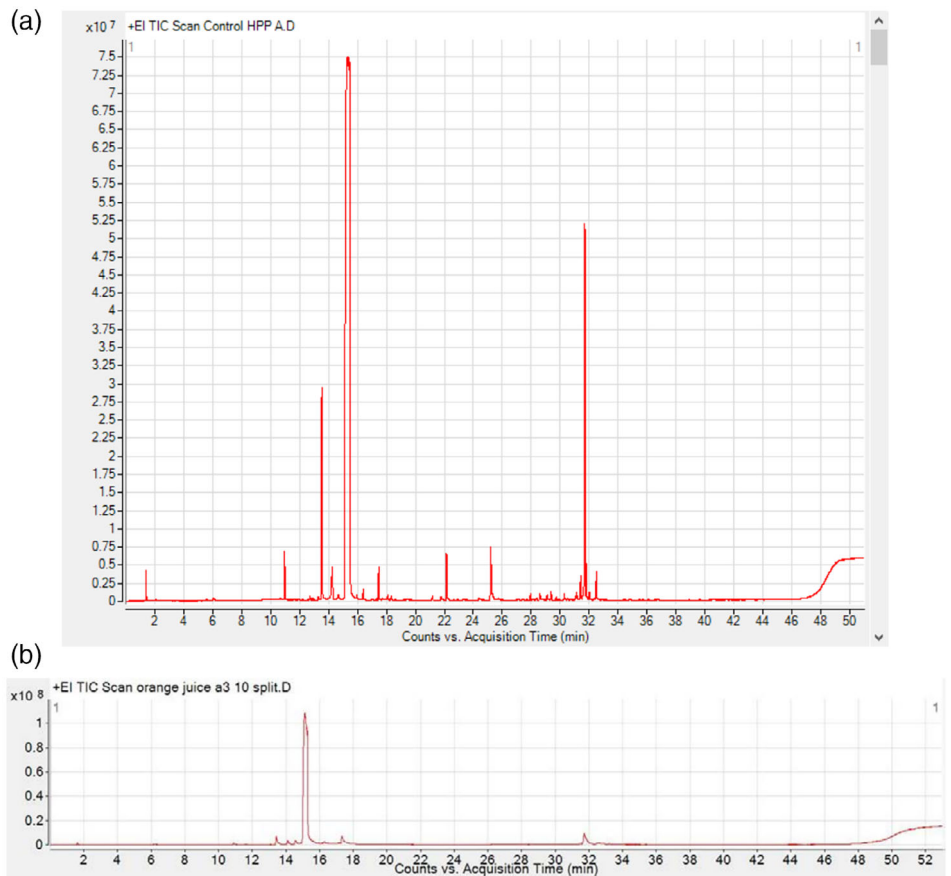
$$p_e = cpu_e SPE(t_f). \quad (4)$$

As the conventional technology is represented by an electrically powered hot water-to-orange juice heat exchanger (Figure 2a) as

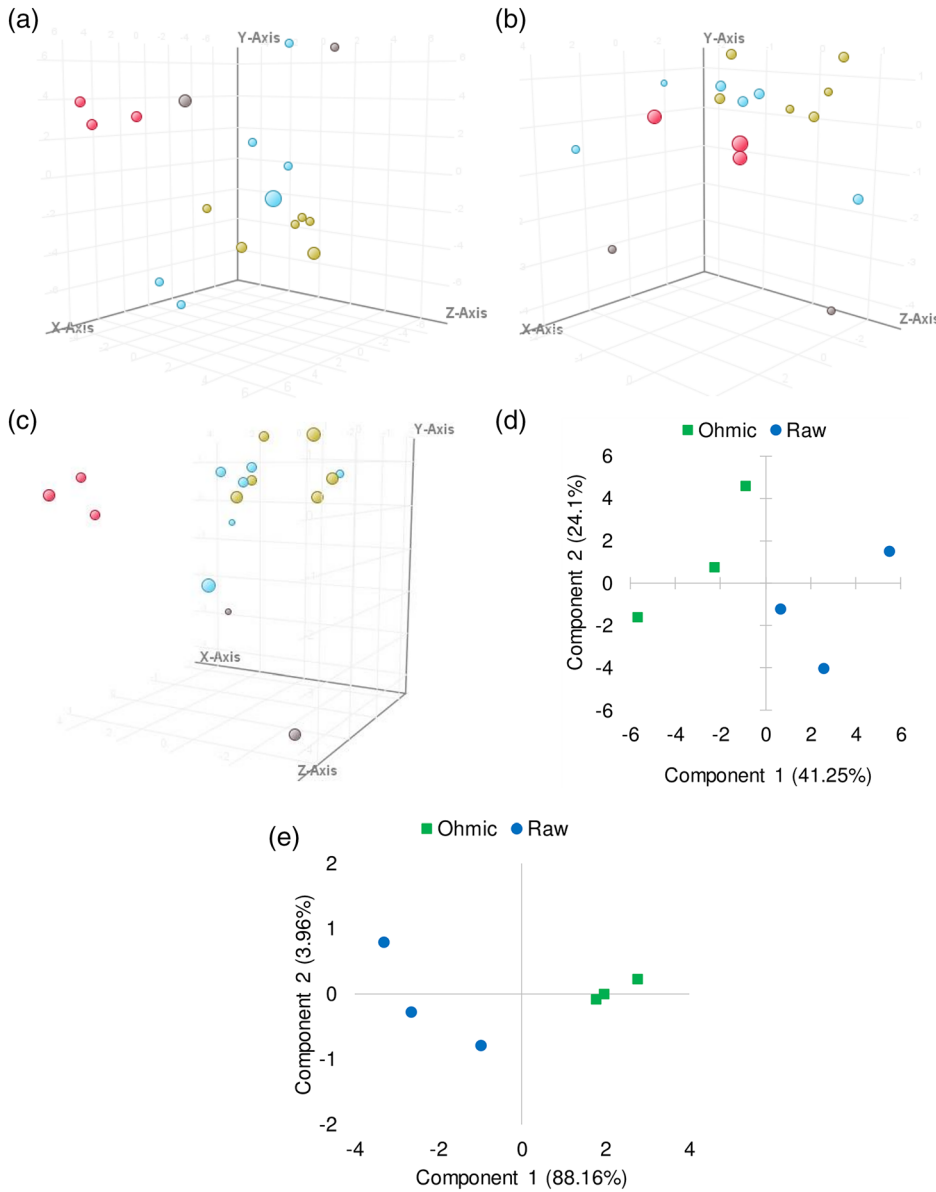
**FIGURE 2** Conventional thermal treatment system (a) based on indirect electrical resistance heating and (b) powered by gas boiler



**FIGURE 3** Representative chromatogram obtained for GC/MS analysis of (a) orange juice samples for control HPP (HPC), HPP, microwave, and UHT processing (all appeared visually similar) and (b) raw and OH-processed orange juice samples (both appeared visually similar)







**FIGURE 4** PCA plot using (a) all sample peaks (for control HPP, HPP, microwave, and CTT samples), (b) selected sample peaks—View 1 (for control HPP, HPP, microwave, and CTT samples), (c) selected sample peaks—View 2 (for control HPP, HPP, microwave, and CTT samples), (d) all sample peaks (for raw and ohmic samples), and (e) selected sample peaks (for raw and ohmic samples)

necessary for equivalent measurement principles across the compared technologies, it is essential to evaluate an equivalent industrially applies gas boiler driven system. This is achieved by replacing the electrical-to-hot water efficiency  $\eta(e, hw)$  of the electric heater EH with the gas-to-hot water efficiency  $\eta(g, hw)$  of a typical boiler (Figure 2b), while the hot water-to-juice efficiency  $\eta(hw, j)$  remains the same. The equation applied is

$$\eta(g, j) = \eta(g, hw)\eta(hw, j) = \frac{\eta(g, hw)}{\eta(e, hw)}\eta(e, j) \quad (5)$$

where  $\eta(e, j) = \eta(e, hw)\eta(hw, j)$  is the overall energy-efficiency of the electrically powered conventional system (Figure 2a) and  $\eta(g, j)$  is that of the gas boiler-driven system (Figure 2b). The specific energy

consumption of the conventional gas boiler-driven system (in terms of the electricity-driven system) is therefore evaluated as

$$SPG(t_f) = SPE(t_f) \frac{\eta(e, hw)}{\eta(g, hw)}. \quad (6)$$

The bracketed terms in Equations (5) and (6) are e (electricity), j (juice), hw (hot water), and g (gas).  $\eta(e, j)$  was determined by dividing CTT juice thermal energy by the corresponding electrical energy measurements.  $\eta(e, hw)$  which is the indirect resistance heating efficiency of the electrical heating element was assigned a typical value  $\eta(e, hw) = 0.8$ , and  $SPG(t_f)$  evaluated for typical upper and lower limits of  $\eta(g, hw) = 0.9$  and  $0.45$ .

The energy cost for pasteurizing 1 L of juice using the gas-driven conventional technology (where  $cpu_g$  is the per-unit gas price) is

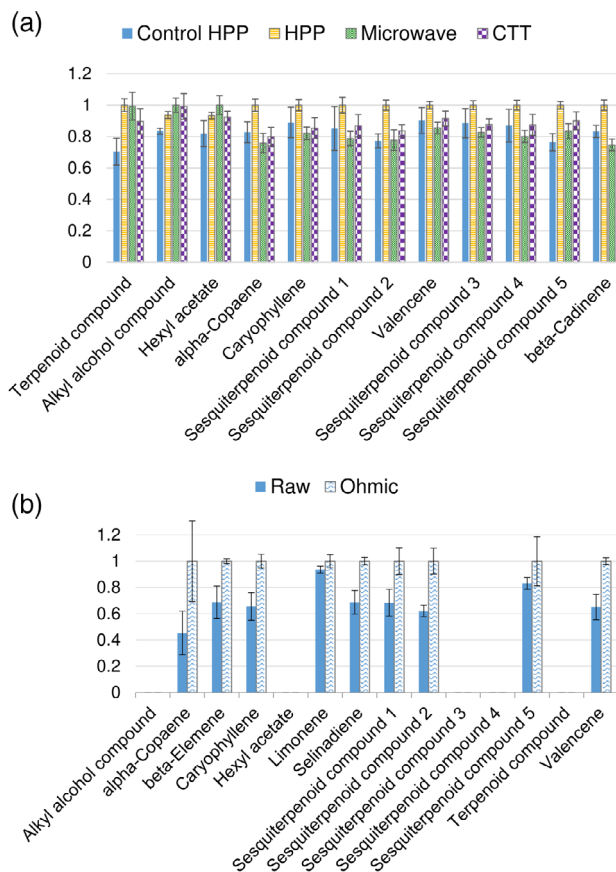
$$p_g = \text{cpu}_g \text{SPG}(t_f). \tag{7}$$

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Flavor compound analysis

For the first phase of the experiments (comparing the MVH, HPP, CTT, and control samples HPC), the GC/MS chromatograms from all the samples appeared to be visually similar to each other (Figure 3a). The chromatograms were therefore subjected to chromatographic deconvolution using software provided with the instrument, to measure the volatile peaks present in the samples. Only peaks detectable in all samples from at least one sample set were measured, to attempt to exclude any artifact or inconsistent peaks in the sample chromatograms. Over 100 potential peaks were measured in this way. All of the data thus obtained was then subjected to principal component analysis, to see if the different sample types could be distinguished from one another. The PCA plot thus obtained (Figure 4a) did indicate that the test HPP samples could be separated from the other samples, and the control HPP samples could be separated from the microwave samples, but that the magnitude of the difference was very small, and the three largest principal components, used to construct the plot, only accounted for comparatively low proportions of the total difference within the sample set (19.52, 16.23, and 10.76%), indicating that any differences represented in the plot were only very slight.

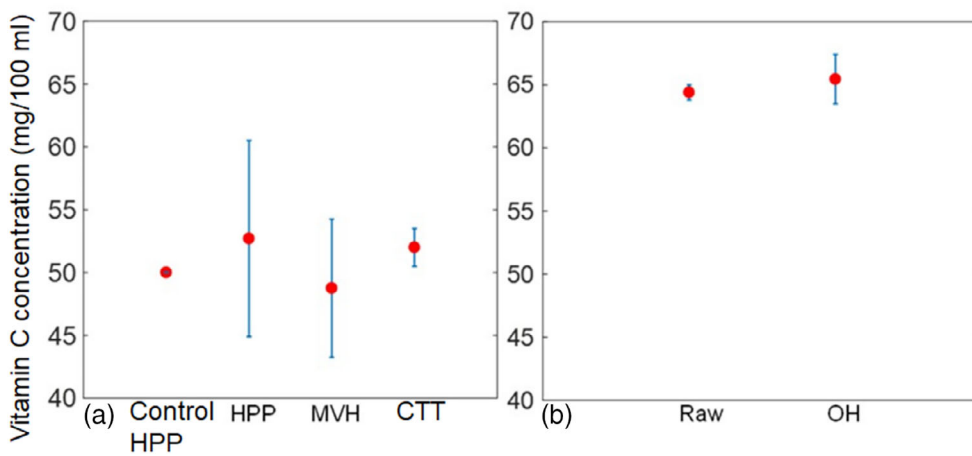
Following the above findings, further statistical treatment of the results was carried out. The data obtained as described above was subjected to an analysis of variance, to single out only those volatile compounds demonstrating statistically significant differences between samples. However, upon carrying out this analysis, none of the peaks were found to possess a corrected  $p$  value of  $<.05$ , indicating that none of the peaks appear likely to exhibit statistically significant differences between the different sample types. Despite this, in order to isolate the peaks demonstrating the greatest potential differences, whether statistically significant or not, the  $p$ -value cut-off was raised to 0.2. Twelve peaks were found to possess  $p$  values lower than 0.2. These peaks were then identified as specifically as possible using the mass spectral library provided with the instrument. Where a peak could not be identified as a specific compound, the type of compound the peak was identified as was noted. The areas of these peaks in the different samples (normalized against the largest peak area of each peak), are expressed graphically as data in Figure 5a. The data was also subjected to principal component analysis, which is shown in Figure 4b, c. Again, it was possible to separate the test HPP samples from the other samples. The control HPP samples could also be separated from the other samples. With this reduced peak list, a greater proportion of the total difference in the sample set was also observable within the first three components (59.06, 16.81, and 9.63%). The test HPP samples appeared to be separated by their slightly higher levels of terpenoid and sesquiterpenoid samples. The control HPP sample appeared to be distinguished by the lower levels of the



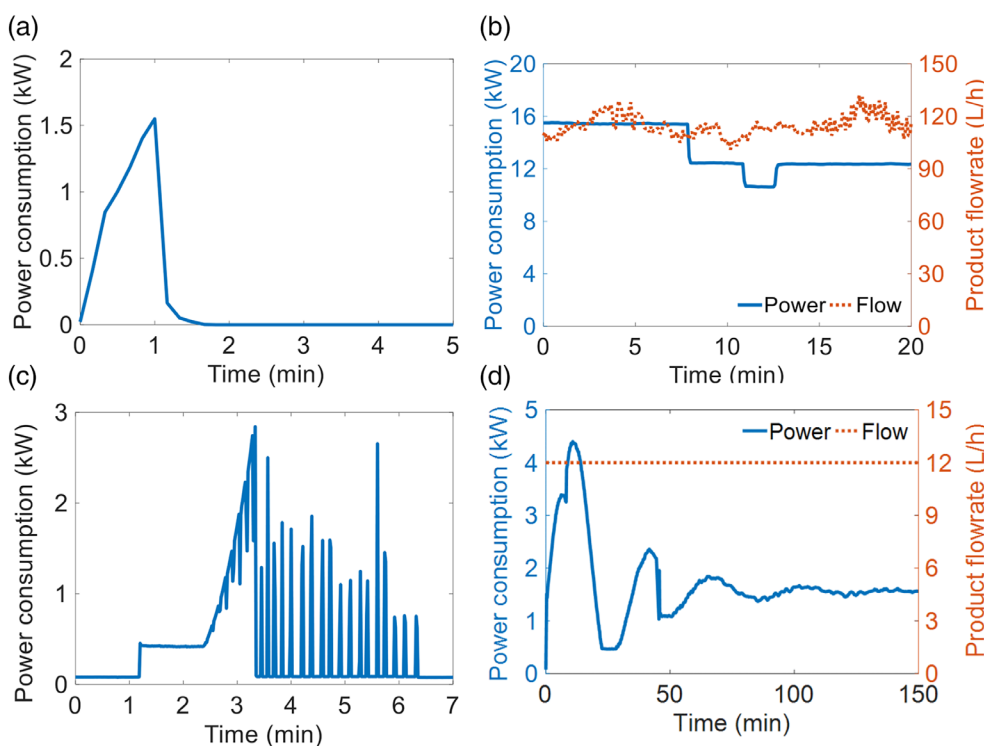
**FIGURE 5** Chart of normalized selected peak areas for flavor compounds (a) MVH, HPP, UHT, and Control HPP and (b) OH and raw

terpenoid compound, the alkyl alcohol compound 3 and hexyl acetate, which of the 12 compounds were the three earliest in the sample chromatogram and hence likely to be the most volatile. However, it was still not possible to distinguish between the microwave and conventionally treated samples.

For the second phase of the experiments (comparing the OH and raw control samples), the chromatograms from the samples were also visually similar (Figure 3b). The chromatograms were subsequently subjected to a combination of chromatographic deconvolution and manual integration using software provided with the instrument in order to measure the volatile peaks present in the samples. The data collected specifically included the peaks previously found to be demonstrating the greatest potential difference between previously analyzed orange juice samples (control HPP, HPP, microwave, and CTT). Only peaks detectable in all samples from at least one of the sample sets were measured, to attempt to exclude any artifact or inconsistent peaks in the sample chromatograms. All of the data thus obtained was then subjected to principal component analysis, to see if the different sample types could be distinguished from one another. The PCA plot thus obtained (Figure 4d) did indicate that the two sample sets could be separated, although the magnitude of the difference between the



**FIGURE 6** Vitamin C concentration for raw/control and processed juices



**FIGURE 7** Power consumption characteristics of (a) ohmic heating system, (b) microwave heating system, (c) high-pressure processing system, and (d) conventional thermal treatment system

sample sets was small, with the largest principal component used to construct the plot only accounting for comparatively low proportions of the total difference within the full set of samples (41.25%), indicating that the differences between the sample sets represented in the plot were only very slight.

Following the above findings, further statistical treatment of the results was carried out. The data obtained as described above was subjected to an analysis of variance, to single out only those volatile compounds demonstrating statistically significant differences between the sample sets. However, upon carrying out this analysis, none of the peaks were found to possess a corrected  $p$ -value of  $<.05$ , indicating that none of the peaks appear likely to exhibit statistically significant differences between the different sample types. Despite this, in order to isolate the peaks demonstrating the greatest potential

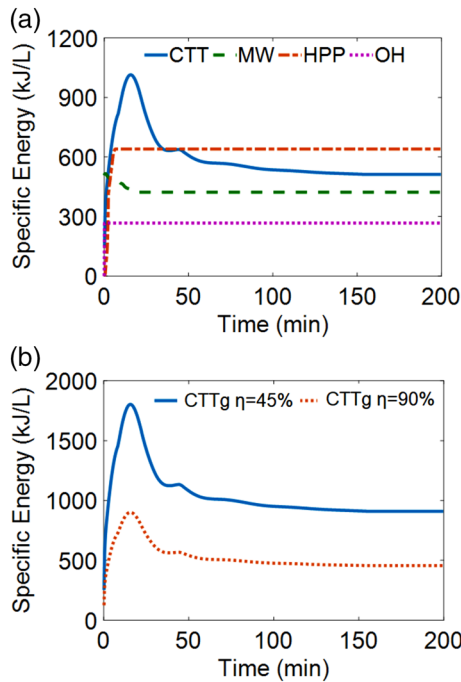
differences, whether statistically significant or not, the  $p$ -value cut-off was raised to 0.2. Seven peaks were found to possess  $p$  values lower than 0.2. These peaks were then identified as specifically as possible using the mass spectral library provided with the instrument. Where a peak could not be identified as a specific compound, the type of compound the peak was identified as was noted. The average areas of the peaks of the replicates for each of the different samples (normalized against the largest peak of each of the peak types) are expressed graphically as data in Figure 5b. It should be noted that although the graph appears to indicate differences between the average peak areas of the samples, the variability between replicates is of a comparable size and as such, the difference is not statistically significant as previously discussed. Of the seven peaks found to demonstrate the greatest potential differences between the two sample sets, five of



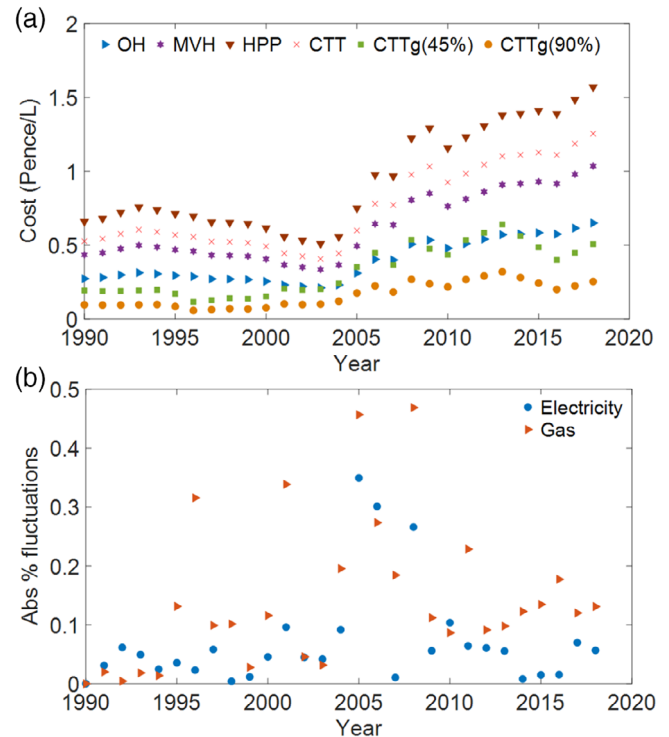
these were previously found to demonstrate the greatest potential differences between the orange juice samples in the previous experiments (control HPP, HPP, microwave, and CTT). The data was also subjected to principal component analysis, which is shown in Figure 4e. Again, it was possible to separate the two sample sets. With this reduced peak list, a greater proportion of the total difference in the sample set was also observable within the largest principal component used to construct the plot (88.16%). The samples in Set B appeared to be separated from sample Set A by their slightly higher levels of terpenoid and sesquiterpenoid compounds.

The results obtained from the control raw orange juice and ohmic heating processed orange juice samples were compared with the

results obtained from the previous samples (control HPP, HPP, microwave, and CTT). Due to the significant time difference between the analysis of the OH and raw samples and the previous experiments (control HPP, HPP, microwave, and CTT), changes in the instrumental conditions limit the scope for direct comparison of the raw peak areas. However, the relative levels of the peaks between samples which were analyzed at the same time can be suitably compared. The peaks found to be demonstrating the greatest potential difference between the samples in this report were all identified as terpenes or sesquiterpenes. All the peaks found to be demonstrating the greatest potential difference between the control HPP, HPP, microwave, and CTT



**FIGURE 8** Specific energy consumption of (a) ohmic, microwave, high-pressure processing, and conventional thermal system (based on indirect electrical resistance heating) and (b) conventional thermal system (gas-powered) at boiler efficiencies of 45 and 90%



**FIGURE 9** (a) Pasteurization energy cost comparison among technologies using UK pricing data (1990–2018) and (b) absolute value of electricity and gas percentage annual fluctuations

**TABLE 1** Prices of fuels purchased by manufacturing industry (Average) in Great Britain, based on DBEIS (2018)

| Year | Electricity cost (p/kWh) | Gas cost (p/kWh) | Year | Electricity cost (p/kWh) | Gas cost (p/kWh) | Year | Electricity cost (p/kWh) | Gas cost (p/kWh) |
|------|--------------------------|------------------|------|--------------------------|------------------|------|--------------------------|------------------|
| 1990 | 3.71                     | 0.76             | 2000 | 3.46                     | 0.61             | 2010 | 6.51                     | 1.72             |
| 1991 | 3.82                     | 0.75             | 2001 | 3.13                     | 0.81             | 2011 | 6.93                     | 2.12             |
| 1992 | 4.06                     | 0.75             | 2002 | 2.99                     | 0.78             | 2012 | 7.35                     | 2.31             |
| 1993 | 4.26                     | 0.77             | 2003 | 2.87                     | 0.80             | 2013 | 7.76                     | 2.54             |
| 1994 | 4.15                     | 0.78             | 2004 | 3.13                     | 0.96             | 2014 | 7.82                     | 2.22             |
| 1995 | 4.01                     | 0.68             | 2005 | 4.22                     | 1.39             | 2015 | 7.93                     | 1.93             |
| 1996 | 3.91                     | 0.46             | 2006 | 5.49                     | 1.77             | 2016 | 7.81                     | 1.58             |
| 1997 | 3.69                     | 0.51             | 2007 | 5.43                     | 1.45             | 2017 | 8.36                     | 1.77             |
| 1998 | 3.67                     | 0.56             | 2008 | 6.88                     | 2.12             | 2018 | 8.83                     | 2.01             |
| 1999 | 3.63                     | 0.54             | 2009 | 7.26                     | 1.89             |      |                          |                  |

**TABLE 2** Levelized cost estimates for projects starting in 2015, technology-specific hurdle rate, £/MWh, highs and lows reflect high and low capital and predevelopment cost estimates (DBEIS, 2016)

|                                    | High    | 68  |   | High    | 121 |
|------------------------------------|---------|-----|---|---------|-----|
|                                    | Central | 66  |   | Central | 93  |
| Combined cycle gas turbine H class | Low     | 65  | Nuclear pressurized water reactor   | Low     | 82  |
| Biomass conversion                 | High    | 88  | Coal ASC with oxy combustion carbon capture and storage                     | High    | 153 |
|                                    | Central | 87  |   | Central | 134 |
|                                    | Low     | 85  |   | Low     | 124 |
| Offshore wind                      | High    | 115 | Combined cycle gas turbine with postcombustion carbon capture and storage   | High    | 123 |
|                                    | Central | 102 |   | Central | 110 |
|                                    | Low     | 90  |   | Low     | 102 |
| Large scale solar PV               | High    | 94  | Open cycle gas turbine 600 MW (500 hr)                                      | High    | 170 |
|                                    | Central | 80  |   | Central | 162 |
|                                    | Low     | 71  |   | Low     | 157 |
| Onshore wind >5 MW UK              | High    | 76  | Coal integrated gasification combined cycle with carbon capture and storage | High    | 171 |
|                                    | Central | 62  |   | Central | 148 |
|                                    | Low     | 47  |   | Low     | 137 |

samples were also all identified as terpenes or sesquiterpenes, except for two peaks one of which was identified as hexyl acetate, and the other as an alkyl alcohol compound. The two nonterpenoid peaks were not of a sufficient size to be quantified in either of the samples in this report, and as such only comparisons of 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 ohmic heating 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 7 of the 11 peaks, and the CTT processed samples exhibit slightly reduced levels of 4 of the 11 peaks. It should be noted however, that as previously discussed none of the peaks were found to possess a corrected  $p$ -value of  $<.05$ , indicating that none of the peaks appear likely to exhibit statistically significant differences between the samples from each set of analyses, and as such any comparison of the relative levels between the samples could be considered not to be statistically significant.

### 3.2 | Total vitamin C analysis

The results for the HPP, MVH, CTT, and control HPP samples as presented in Figure 6a show that the variation in vitamin C levels within each process was much greater than the variation between processing types which was not statistically significant ( $p > .05$ ). The outcome was similar on comparing the OH-treated and raw juice samples as shown in Figure 6b. No significant differences between the samples are observed. Overall from Figure 6a,b, no significant vitamin C degradation between the control/raw and all the processed samples is observed. The innovative and conventional technologies therefore compete favorably with fresh products in this regard.

### 3.3 | Energy performance and economics

Figure 7 a–d shows the power consumption characteristics of the OH, MVH, HPP, and CTT systems, respectively. For the continuous processes (MVH and CTT in Figure 7b,d), the flowrates are also shown, plotted on the same axes. By performing the relevant integration operations using Equations (2) and (3), the specific energy consumption characteristics of each of the processes are as shown in Figure 8a. Although the electricity-driven innovative processing technologies are inherently fast, the times of all processes are shown extended in Figure 8a to the transient time of the slowest process, the CTT system for easy visualization of the comparison. Note that the processing speed of the CTT system is limited by the hot water-to orange juice heat transfer rate, whereas the innovative processes are volumetric and so much faster. It is observed that the OH process has the best performance with a specific energy consumption of 265 kJ/L. The MVH system comes next with 422 kJ/L, while the electricity-driven CTT system consumes 511 kJ/L. The HPP system consumes 640 kJ/L. An equivalent gas-powered conventional system (CTTg) consumes 910 kJ/L at 45% boiler efficiency and 455 kJ/L at 90% boiler efficiency (Figure 8b). The CTTg figures are based on primary energy (gas). No heat recovery was considered in all the processes.

Apart from product safety and quality, energy pricing is perhaps, the most important factor for industries in deciding between the innovative and conventional technologies. This again is country-specific. Table 1 shows the UK annual average industrial electricity and gas cost data (1990–2018), derived from the quarterly data for all categories of industries (DBEIS, 2018). These represent the  $cpu_e$  and  $cpu_g$  parameters in Equations (4) and (7), respectively. Using this data in conjunction with the experimentally determined specific energies, the pasteurization energy costs per liter associated with each of the technologies is shown in Figure 9a. In spite of the significant efficiency

gains of the innovative technologies, the high cost of electricity makes them less economical (in terms of pasteurization energy costs per liter of product) than gas-powered conventional thermal processing systems. A significant observation, however, is that electricity prices are more stable than gas prices (Figure 9b), which is important for forecasting and planning purposes. There is a strong correlation between electrical energy prices and energy mix, quantifiable by an important figure of merit, the so-called LCOE. The LCOE is the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output over that lifetime and can be regarded as the average minimum price at which electricity must be sold in order to break-even over the lifetime of the project (Ouyang & Lin, 2014). UK LCOE data presented in Table 2, for projects starting in 2015 (DBEIS, 2016), show that in general, the renewable technology options and the CCGTs have much lower costs than the conventional fossil fuel-based electricity generation technologies. Similar conclusions can be reached with projected values up until 2025. The UK energy mix data (OFGEM, 2018) shows that the proportion of grid electricity from renewable sources has been on the ascendancy since 2006, and currently stands at about 30%. This trend is expected to continue, given the strong emission reduction policies of the UK government. With the lower LCOE of the renewable generation technologies, per-unit electricity prices are expected to drop in the long-term, as more grid electricity is sourced renewably and fossil-based systems switch to the more efficient use of natural gas, via CCGT. It may not be long before the innovative electricity-driven technologies become more economical than conventional thermal treatment in terms of pasteurization energy costs per liter.

In translating to production-type scenarios, it is important to note that specific energies are sensitive to equipment design and operating conditions. Atuonwu and Tassou (2018a, 2018b) using a theoretical model show that HPP energy performance improves with scale and vessel fill ratio. Current industrial HPP systems operate usually in batch mode, which increases labor costs. Industrial ohmic heaters are of the continuous-flow type, which are about 20% more efficient for liquid food pasteurization than the batch system studied in this work as the power losses due to voltage switching does not occur (Atuonwu et al., 2018). Wang et al. (2015) also showed empirically that the energy performance of microwave heaters improves with scale. As industrial energy consumption data is not usually available due to nondisclosure (Atuonwu et al., 2018; Toepfl, Mathys, Heinz, & Knorr, 2006), experimental methods are required to evaluate each industrial case. The methodology developed and applied in this work will be useful in evaluating and comparing any sets of pasteurization technologies at industrial scale. For pasteurization of conductive heat transfer-limited and highly heterogeneous solid foods for example, meat, fish products, soups, vegetables, and so forth, the energy and quality advantages of the innovative electricity-driven processes over CTT are expected to increase due to their fast, volumetric nature.

## 4 | CONCLUSION

Sensory and nutritional quality (flavor compounds and vitamin C) as well as energy performance and cost aspects have been evaluated in one step for conventional thermal and innovative (high pressure, microwave, and ohmic) processing of orange juice under commercially representative conditions. No significant differences are observed in the quality attributes of the processed product across all the technologies. This is likely due to a combination of the mild treatment conditions (<80°C, and far less for the high-pressure process) and short processing times employed. While significant efficiency gains are made due to electrification using the electricity-driven innovative technologies (especially the ohmic process), the higher per-unit costs of grid electricity results in poorer energy economics relative to conventional gas-fired technology. UK LCOE data suggests that as more of grid electricity is sourced renewably, the innovative technologies will eventually become more economical, in addition to the significant greenhouse gas emission reductions per liter of product. Energy cost stability is also enhanced using the electricity-driven technologies, which is important for forecasting. The innovative electricity-driven technologies are thus promising alternatives to conventional thermal pasteurization.

## ACKNOWLEDGMENTS

The work presented in this article received funding from the Research Councils UK (RCUK) for the establishment of the RCUK Centre for Sustainable Energy Use in Food Chains (CSEF) through EPSRC grant No: EP/K011820/1. The authors acknowledge the financial support from the Research Councils UK Energy Program and support received from CSEF. All data used are given in the article but the corresponding author can be contacted for additional information or data if required.

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**How to cite this article:** Atuonwu JC, Leadley C, Bosman A, Tassou SA. High-pressure processing, microwave, ohmic, and conventional thermal pasteurization: Quality aspects and energy economics. *J Food Process Eng.* 2019;e13328. <https://doi.org/10.1111/jfpe.13328>