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Powering up brewing: ohmic heating's effect on the extraction of key sensory compounds from hop pellets

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This study evaluates ohmic heating (OH) technology as an alternative to wort boiling in brewing and its impact on the extraction of key sensory compounds in beer—essential oils, alpha-acids, and polyphenols—from hop pellets. Conventional (C) boiling, performed using a water jacket, served as the control, while OH was applied at three electric field intensity ranges: 4–5 V cm^{−1} (OH5), 8–11 V cm^{−1} (OH11) and 22–26 V cm^{−1} (OH26). OH treatments influenced extraction/reaction kinetics when compared with C boiling, reducing total boiling time to 15 min, demonstrated by the absence of significant differences between the international bitterness units (IBU) of OH5 (86.38 ± 0.72), OH11 (89.21 ± 0.79) and OH26 (90.78 ± 2.83) after 45 min and the IBU of C (91.49 ± 4.98) after 60 min of boiling. Moreover, statistically significant (*p* < 0.05) higher IBU were observed for all OH conditions compared to C after 30 and 45 min of boiling. Kinetic differences were also observed for polyphenol concentrations, evident after 60 min of boiling, with C standing out with higher values (210.11 ± 6.01 mg L^{−1}) over OH5 (165.97 ± 1.36 mg L^{−1}), OH11 (177.09 ± 8.58 mg L^{−1}) and OH26 (175.48 ± 12.66 mg L^{−1}), suggesting that electric fields contribute to a faster decrease in polyphenol content against C boiling. Gas chromatography-mass spectrometry (GC-MS) analysis of essential oils revealed that longer boils reduce the levels of essential oils in both C- and OH-treated worts. Myrcene and humulene retention is not influenced by the chosen heating method. However, regarding linalool and geraniol, the higher electric field intensities of OH11 and OH26 resulted in a decrease of these essential oils' levels, while C boiling and OH 5 boiling, promoted their retention in the final beer. Results suggest that OH treatments could be employed in brewing as a novel boiling technology. OH promotes uniform and rapid heating, faster bitterness development and increased hop utilization, less haze and astringency, and potential modulation of the hoppy flavours and aromas in beer. OH further demonstrated its potential to reduce processing time and energy consumption, highlighting this technology as a promising and sustainable alternative to conventional boiling methods.

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Sustainability spotlight

The brewing industry is constantly seeking more sustainable and energy-efficient processes to reduce its environmental footprint. This study evaluates ohmic heating (OH) technology as an alternative to conventional boiling in the brewing process, with particular emphasis on its effects on the aroma profile, specifically concerning alpha-acids, polyphenols, and essential oils. OH technology presents potential benefits in terms of energy savings and processing time reduction, without impacting the beer's quality, thus contributing to a more efficient use of resources. By optimizing heating conditions in brewing, this work is aligned with the UN's Sustainable Development Goals, more precisely Goal 7 (Affordable and Clean Energy) and Goal 12 (Responsible Consumption and Production). Adopting cleaner and more efficient technologies may significantly reduce energy consumption and waste, promoting a more sustainable brewing industry.

1 Introduction

Beer is one of the most consumed alcoholic beverages worldwide, largely appreciated by people across a wide range of ages, and diverse social and cultural backgrounds.¹ Recent global

beer consumption data highlight the scale of the brewing industry, which includes both the industrial and craft segments, with a combined production of 187.9 million kL of beer in 2023.² This represents an increase of 0.1% from the previous year, underscoring the significant economic impact and increasing popularity of beer worldwide.

Brewing is a continuously evolving science that harmonizes tradition and innovation to meet the growing demand for beers with enhanced sensory qualities. This dynamic field seeks to

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develop novel, fresh, and more complex products, offering a richer spectrum of flavours and aromas while maintaining quality and consistency.

Beer is made from four main ingredients: water, malted cereals, hops and yeast.³ These are incorporated at different stages of the brewing process. During mashing, milled malt is added to heated water, converting starches into fermentable sugars and producing wort.⁴ After separation of malt husks from the wort, the wort is boiled.⁵ At this point, hop products (*e.g.* hop cones, hop pellets, hop extracts, *etc.*) are added, releasing and solubilizing key sensory compounds such as alpha-acids, polyphenols and essential oils. Hop alpha-acids, which are initially insoluble in wort, undergo isomerization reactions during boiling, rearranging into soluble iso-alpha-acids that impart bitterness and contribute to the foam stability of beer.^{6,7} Polyphenols, already present in wort through malt, are also extracted from hops during boiling. They contribute to flavour stability due to their antioxidant properties, cause haze formation through polyphenol-protein complexes, enhance beer's bitterness and astringency, and are also associated with the health benefits of moderate beer drinking.^{8,9} In turn, hop essential oils are crucial for beer's flavour and aroma, contributing to floral, citrus, spicy, and resinous notes that shape different beer styles by influencing their sensory complexity and overall balance.^{10,11} After boiling, the wort is then cooled to fermentation temperature, where yeast cells convert fermentable sugars into ethanol, carbon dioxide and flavour-active compounds that contribute to beer's flavour and aroma.^{12,13} Lastly, beer is matured, filtered if necessary, carbonated and packaged for distribution and consumption.^{14,15}

Throughout the brewing process, thermal steps play a crucial role in beer production, particularly in the boiling stage, which is the most energy-intensive step of the whole brewing process.¹⁶ Boiling has emerged as one of the most important steps of brewing, since it deeply shapes the microbiological, physicochemical and sensory properties of wort and consequently beer. In both industrial and craft brewing sectors – as in many other food processing industries – wort boiling is primarily carried out using one of the following methods: direct fire heating, steam heating or electrical heating (Table S1).¹⁷ Direct fire heating systems, popular choices of small craft breweries and home breweries, resort to open flames from gas burners (sustained by natural gas or propane) which are positioned beneath the boiling kettle. These systems offer fast heating, ease-of-use and low installation investments. However, direct fire heating offers low heating efficiency, can pose fire safety issues, cause scorching of the wort, and in the long term, might become more expensive than other heating delivery methods.^{17–19} Steam heated systems use high-pressure steam, generated by a boiler, through internal coils or outer jackets that are in contact with the boiling kettle. This heating method is undoubtedly the most common way of heating kettles at an industrial scale, given the precise temperature control, and the efficient and uniform heat distribution attained. Due to the need to build a boiler system and a built-in thermal jacket/coil in the kettle, it is the costliest heating method of all of the ones outlined above.^{17,18,20}

Electric heating systems – commonly used in small commercial brewing production units (200–1000 L) and home breweries – make use of electrical resistances in contact with wort or integrated in the kettle walls. These types of heating systems allow a precise temperature control without needing the installation of a boiler or gas system, are easily automated and are very energy efficient. The downsides of electric systems are the high up-front cost of a kettle equipped with electric resistances, as well as production cost due to electricity consumption. Additionally, the heating speed of electric heating can be slow, extending brewing times in the brewery.^{17,21}

These operations pose challenges regarding energy and time efficiency. As a result, they not only reduce profitability but also increase the environmental impact, making sustainability and modernization crucial considerations for the brewing industry.²² Ohmic heating (OH) technology has emerged in scientific research and the food processing industry as a promising solution to overcome the limitations of traditional heating methods, in product quality and processing efficiency.^{23,24} The principle of OH technology is quite straightforward: alternating current is delivered through electrodes, which are in contact with a food product, allowing the electrical current to flow through the food material. The food's natural electrical resistance converts the electrical energy directly into heat, in accordance with Joule's law.²⁵ By directly generating heat within the food product, OH minimizes thermal gradients, shortens processing time and prevents localized overheating that can cause food scorching.²⁶ This contributes to enhancing the sensory, functional and nutritional properties of food products processed by OH technology.²⁷ Since heat is produced internally, more than 90% of electrical energy can be converted to heat, minimising losses. This makes OH more energy-efficient than traditional heating methods, where heat is lost throughout the system.²⁸ Moreover, such technology could be regarded as environmentally friendly, as it may be powered by renewable energy sources (*e.g.* hydro, solar, wind, *etc.*). Several authors have already reported that OH technology is highly effective for microbial inactivation, by combining thermal and non-thermal effects.²⁹ The presence of an electric field can promote microbial cell damage by means of electroporation – a mechanism which induces pore formation in cell membranes – ultimately leading to loss of integrity and consequent cell lysis.³⁰ Besides microbial inactivation, induced electroporation increases membrane cells' permeability, facilitating the mass flow of intracellular compounds between the interior of cells and the surrounding solution.³¹ Increased extraction yields of polyphenols and oils have already been demonstrated to occur, through the application of electric field technologies in plant products, similarly to hop pellets.^{32,33}

By eliminating traditional boilers and reducing water consumption, OH technology supports decarbonization and the sustainable use of resources.³⁴ Besides the large number of OH's strengths, this technology also displays its own limitations, as displayed in Table S1. These consist of high up-front costs, the requirement for foods exhibiting good electrical conductivity, and electrode fouling when electrolysis reactions are promoted at low electrical frequencies.³⁵



Despite the growing interest in energy-efficient technologies for brewing, OH technology remains largely unexplored throughout the different stages of the brewing process. While this method has demonstrated significant advantages in other food processing applications, no studies to date have specifically evaluated its potential for wort boiling. Therefore, this study aims to address this gap by investigating the impact of this technology on the extraction of key compounds from hop pellets, particularly those that influence the sensory characteristics, such as bitter acids, essential oils, and polyphenols.

2 Materials and methods

2.1 Ohmic heating equipment

Wort boiling was conducted in the same reactor, both for OH treatment and control, setting aside differences related with reactor design and operations after lautering. An ohmic reactor was used for wort boiling, encompassing the insertion of two stainless steel electrodes establishing a treatment volume of 30 mL. It was equipped with a heating/cooling water-jacket for control (conventional) wort boiling treatments. A type K thermocouple (Omega Engineering, Inc., Stamford, USA) with a precision of ± 1 °C, placed at the geometric centre of the sample volume, was used to monitor temperature variations. The thermocouple was connected to a data logger (USB-9161, National Instruments Corporation, Austin, USA). The reactor was powered from an amplifier system (Peavey CS3000, Meridian, USA), which converted the electrical current supplied by a function generator (Agilent 33220A, Penang, Malaysia). Energy consumption was measured using a portable multimeter (Fluke, Everett, WA, USA). This setup reported real-time information to an acquisition system, which allowed recording of electrical and thermal data. A graphical representation of the system is presented in Fig. 1.

2.2 Boiling regimes and sample handling

Four different procedures of atmospheric wort boiling were performed with 30 mL of wort: Conventional (C) boiling, ohmic heating (OH) boiling sustained by an electric field intensity ranging from 4–5 V cm⁻¹ (OH 5), OH boiling sustained by an electric field intensity ranging from 8–11 V cm⁻¹ (OH11), and

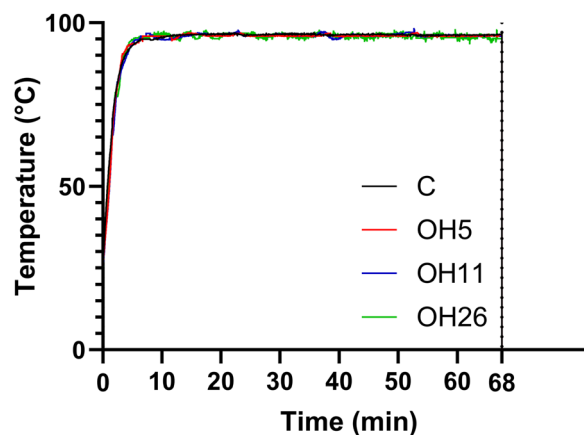


Fig. 2 Thermal profile of wort boiling under different heating conditions: conventional (C) boiling represented in black, ohmic heating (OH) boiling at 4–5 V cm⁻¹ (OH5) represented in red, OH boiling at 8–11 V cm⁻¹ (OH11) represented in blue, and OH boiling at 22–26 V cm⁻¹ (OH26) represented in red.

OH boiling sustained by an electric field intensity ranging from 22–26 V cm⁻¹ (OH 26). Wort preparation information is available in SI A1. Electrical 25 kHz sine waves were delivered for OH treatments, avoiding electrochemical side-reactions. Moreover, for all the OH boiling conditions, the heating of the wort samples from room temperature (25 ± 1.5 °C) to the final temperature (96 ± 1 °C), was conducted with varying electric field intensities which allowed the thermal profile recorded for C boiling to be simulated, as presented in Fig. 2.

As soon as each treatment reached boiling temperature, 100 ± 10 mg of hop pellets were added to the treatment reactor, setting the beginning of the boiling process, which was carried out for a total of 60 min at a constant temperature of 96 °C. Hop variety information is available in SI A2. A magnetic stirring bar, with a size of 0.5 cm, set at a speed of 200 rpm, was also added to the reactor in the beginning of boiling, to simulate the naturally occurring turbulence inside a brewing boiling kettle.

Small aliquots of 1 mL were collected for bitterness and polyphenolic content assessment at 0, 15, 30, 45 and 60 min of boiling. Additionally, aliquots of 5 mL were collected for essential oil characterization at 0, 20, 40 and 60 minutes of boiling. After sampling, all the collected aliquots have been centrifuged at 5000 rpm \times 5 min ($1400 g \times 5$ min) and immediately stored in a refrigerator at 5 °C, before analysis, to ensure the preservation of the compounds of interest to be analysed.

2.3 Bitterness determination

The assessment of the bitter content of the wort samples was accomplished in accordance with the EBC 9.8 method,³⁶ modified for a smaller sample size. To achieve this, 200 μ L of beer's wort was used, preserving all the remaining reagents' proportion. Moreover, the vigour and time of shaking required in this method were established, by measuring the absorbance of the iso-octane layer at 275 nm, until no further increase in absorbance was observed.

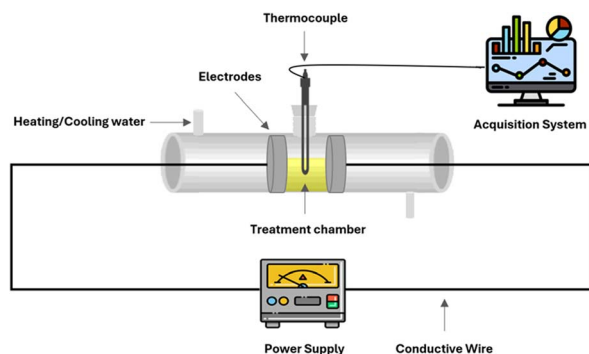


Fig. 1 Schematic representation of the ohmic heating system used for wort boiling (redrawn from ref. 28).



The absorbance of the organic layer was measured at 275 nm using a spectrophotometer (SpectraMax® ABS Plus, California, USA), and the results have been expressed as International Bitterness Units (IBU), following eqn (1):

$$\text{Bitterness (IBU)} = 50 \times \text{Abs}_{275} \quad (1)$$

2.4 Total polyphenols determination

The total content of polyphenols in the wort samples was evaluated according to the EBC 9.11 method,³⁷ modified for a smaller sample size. For this purpose, 500 µL of sample was used (250 µL for the sample and 250 µL for the blank), preserving all the remaining reagents' proportion.

The measurement of absorbance of both the sample and blank was performed at 600 nm in a spectrophotometer (SpectraMax® ABS Plus, California, USA), and the results in terms of polyphenol content were obtained according to eqn (2):

$$\text{Polyphenol content (mg L}^{-1}\text{)} = 820 \times \text{Abs}_{600} \quad (2)$$

2.5 Essential oils determination

2.5.1 LLE/GC-MS approach. Evaluation of volatile compounds, namely essential oils, in wort samples was accomplished by performing a liquid-liquid microextraction followed by gas chromatography-mass spectrometry (LLME/GC-MS), as described by Coelho *et al.*³⁸

For this purpose, 4 mL of beer's wort was added to 4 mL of ultrapure water (Milli-Q® Reference System, Merck, Darmstadt, Germany) in a 10 mL culture tube (Pyrex, USA) with a magnetic stirring bar inside. 100 µL of internal standard, 4-nonanol (55 mg L⁻¹), were also added, together with 400 µL of dichloromethane for the extraction of the volatile fraction. The extraction was promoted by stirring the samples at room temperature for 15 min, ensuring uniform dispersion of the solvent. After the 15 min of agitation, the samples were placed in a cooler at 0 °C for 10 min to disrupt the formed emulsions, magnetic stirring bars were removed from the tubes, and the organic phase separated through centrifugation (2000 rpm × 5 min). The extracts were then recovered, dehydrated with anhydrous sodium sulphate, to eliminate water traces in the extract, and stored in a freezer at -20 °C, prior to analysis.

2.5.2 Chromatographic analysis. To quantify volatile compounds, namely essential oils, a gas chromatographic analysis was performed in a GC-MS composed of a GC-2030 gas chromatograph equipped with an AOC-20i Plus auto injector and a QP2020 NX single quadrupole gas chromatograph mass spectrometer from Shimadzu (Kyoto, Japan). A Stabilwax-MS (Restek, Pennsylvania, USA) capillary column (30 m × 0.25 mm, 0.25 µm film thickness) was used for the chromatographic runs. The temperature of the injector and the MS transfer line were both set to 250 °C. Oven temperature was held at 60 °C, for 5 min, then programmed to rise from 60 °C to 250 °C, at 3 °C min⁻¹, and then held for 20 min at 260 °C. The carrier gas was helium GHE4× (Praxair, Maia, Portugal), at a constant flow rate of 1.66 mL min⁻¹. A 1 µL injection was made in the split-less mode, kept

for 30 s, followed by a constant split of 1 : 20. The detector was set to an electronic impact mode (70 eV) with an acquisition range (*m/z*) from 29 to 360 at an acquisition rate of 300 ms.

2.5.3 Identification of volatile compounds. The identification of essential oils was performed using GCMS Real Time Analysis software (Shimadzu, Kyoto, Japan), by comparing retention indexes and mass spectra with those of reference compounds available in the National Institute of Standards and Technology (NIST) database. Results were expressed as 4-nonanol equivalents.

2.6 Sustainability evaluation

To assess the environmental impact of C and OH boils, the E-factor, Process Mass Intensity (PMI), and energy consumption were calculated based on eqn (3)–(5), respectively, following referenced approaches:^{39–41}

$$E(\text{factor}) = \frac{\text{Mass of waste(kg)}}{\text{Mass of final product(kg)}} \quad (3)$$

$$\text{PMI} = \frac{\text{Mass of consumables(kg)}}{\text{Mass of final product(kg)}} \quad (4)$$

$$\text{Energy consumption} = \frac{\text{Electric consumption(kWh)}}{\text{Mass of final product(kg)}} \quad (5)$$

2.7 Statistical analysis

Univariate and multivariate statistical analyses were performed using GraphPad Prism (version 10, GraphPad Software, California, USA) and OriginPro – (OriginPro, Version 2021, OriginLab Corporation, Northampton, MA, USA), respectively. Exhibited results are expressed as mean ± standard deviation (SD) calculated based on three replicates of the same treatment. Statistical significance was assessed using one-way ANOVA, followed by Tukey's *post hoc* test to perform pairwise comparisons between different boiling treatments, at the same time point. Statistical significance was considered at *p* < 0.05, for declaring a statistically significant result.

3 Results and discussion

3.1 Bitterness

The data regarding IBU values (Table S2) are displayed in Fig. 3 and show bitterness variation during the four distinct boiling regimes tested: conventional (C) boiling, ohmic heating (OH) boiling using an electric field intensity ranging from 4–5 V cm⁻¹ (OH5), OH boiling using an electric field intensity ranging from 8–11 V cm⁻¹ (OH11), and OH boiling using an electric field intensity ranging from 22–26 V cm⁻¹ (OH26).

At the beginning of boiling, low but measurable IBU values across all the different treatments have been detected, despite no hops being added at this stage. These values are likely due to interfering species (*e.g.* polyphenols, saccharin and salicylic acid), that can be extracted from wort into iso-octane, absorbing UV light.⁴² Despite this, bitterness levels (3.08–3.81 IBU) did not differ significantly between treatments (*p* > 0.05), setting



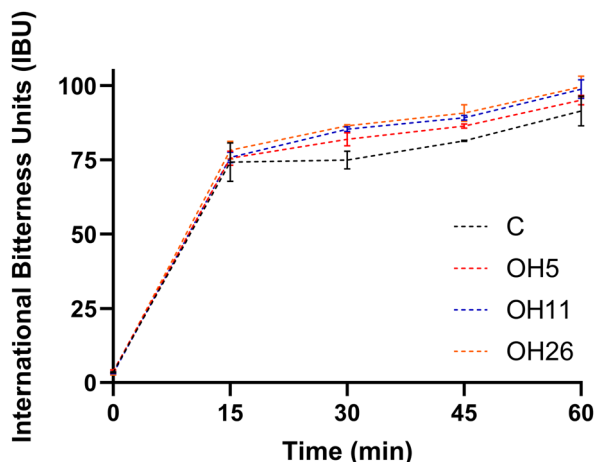


Fig. 3 Evolution of bitterness levels (IBU) in wort samples monitored at 15-minute intervals, over a 60-minute boiling period. Boils were performed through conventional (C) heating, in black, and ohmic heating (OH) methods using different electric field intensities: 4–5 V cm^{-1} (OH5) in red, 8–11 V cm^{-1} (OH11) in blue, and 22–26 V cm^{-1} (OH26) in green. Points represent mean values \pm standard deviation ($n = 3$), presented in Table S2.

a uniform baseline for all samples before hops were added to the boiling wort. In the first 15 min of boiling, all the samples developed a substantial increase in bitterness levels. This initial phase accounted for 73–81% of the total bitterness measured at the end of boiling, indicating that most bitterness develops early. At 30 and 45 min of boiling, all OH treatments (OH5, OH11, OH26) produced significantly more bitter worts than C boiling. At the end of boiling (60 min), this trend prevailed; however, the difference was not statistically significant ($p > 0.05$) – see Fig. 3. These observations constitute strong evidence that the presence of electric fields can promote a faster development of bitterness. Fig. 4 illustrates the relationship between electric field intensity and bitterness development. It should also be

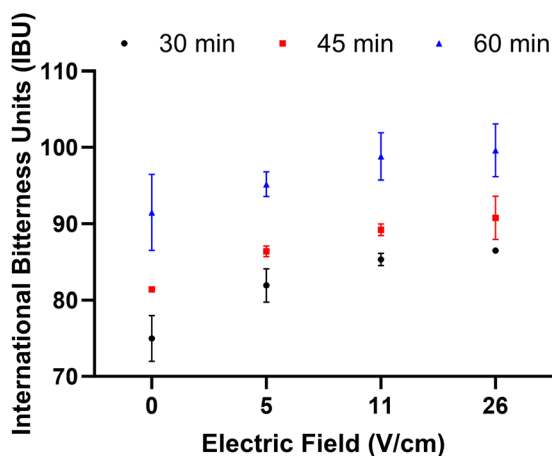


Fig. 4 Evolution of bitterness levels (IBU) in wort samples, with different electric field intensities: 0 (conventional), 4–5 (OH5), 8–11 (OH11) and 22–26 (OH26) V cm^{-1} , at three significant time frames (30, 45 and 65 minutes).

mentioned that for the same time frame, higher electric field intensities resulted in increased wort bitterness. This suggests that bitterness development may be influenced not only by the presence of electric fields, but also by their intensity.

The consistent trend observed during the 60-minute boil suggests a relationship between electric field intensity and bitterness development. So far, the potential influence of electric field processing on alpha acid extraction has only been demonstrated for electric field intensities in the kV cm^{-1} range, at room temperature, and using organic solvents. Ntourtoglou *et al.*⁴³ reported that applying pulsed electric fields in the kV cm^{-1} range to bitter hop pellets (similar to the ones used in this study) increased by 20% the extraction rate of alpha-acids to methanol at 25 °C.

At the end of 60 min of boiling, all treatments reached their peak bitterness values, with OH26 showing the highest level (99.61 ± 3.48), followed closely by OH11 (98.81 ± 3.10), OH5 (95.20 ± 1.62), and lastly, C (91.49 ± 4.98). These bitterness levels are in accordance with typical double, triple and imperial India Pale Ale (IPA) beers.⁴⁴ The absence of statistically significant differences ($p > 0.05$) between the bitterness achieved after 45 min through any OH boil (OH5, OH11 and OH26) and the bitterness of worts after 60 min of C boiling suggests that OH technology, under electric field intensities such as that applied in this study, may allow a reduction in total boiling time. These results indicate that electric fields primarily influence the rate of alpha-acids isomerisation and/or their extraction from hop pellets. In this study, only electric fields of moderate intensity ($<1000 \text{ V cm}^{-1}$) were applied, which allowed a controllable OH effect for the boiling stage.

3.2 Total polyphenols

Total polyphenols content data, presented in Table S2, were used to set up Fig. 5, which displays total polyphenols content variation during the four distinct boiling regimes tested:

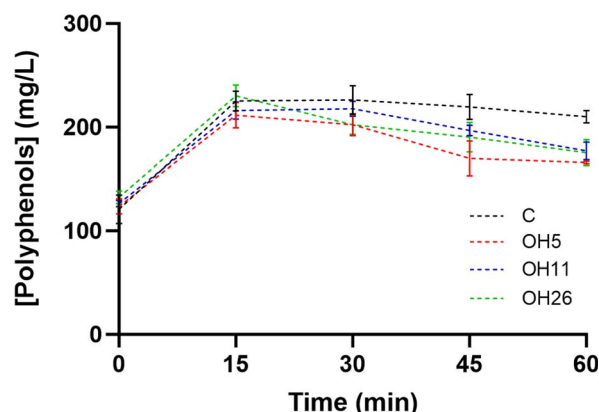


Fig. 5 Evolution of polyphenol concentration (mg L^{-1}) in wort samples monitored at 15-minute intervals, over a 60-minute boiling period. Boils were performed through conventional (C) heating, in black, and ohmic heating (OH) methods using different electric field intensities: 4–5 V cm^{-1} (OH5) in red, 8–11 V cm^{-1} (OH11) in blue, and 22–26 V cm^{-1} (OH26) in green. Points represent mean values \pm standard deviation ($n = 3$), presented in Table S3.



conventional (C) boiling, ohmic heating (OH) boiling using an electric field intensity ranging from 4–5 V cm⁻¹ (OH5), OH boiling using an electric field intensity ranging from 8–11 V cm⁻¹ (OH11), and OH boiling using an electric field intensity ranging from 22–26 V cm⁻¹ (OH26).

At the beginning of boiling, before the addition of hop pellets, all treatments exhibited similar total polyphenol concentrations (ranging from 124 to 132 mg L⁻¹), with no statistically significant differences among them ($p > 0.05$). This confirms that the initial polyphenol content of the wort samples was comparable across different treatments. The initial presence of polyphenols in the samples has its origin in the barley malt used to brew this beer.⁴⁵ Moreover, the initial polyphenol content matches typical values found in light-coloured wort before boiling.⁴⁶ A rapid extraction of hop's polyphenols occurred within the first 15 min of boiling across all boiling methods. Concentrations nearly doubled, driven by the considerable hop dosage added at the start of the boil. Polyphenol concentrations peaked between 15 and 30 min in all treatments. During this period, no statistically significant differences ($p > 0.05$) were observed, indicating that polyphenol levels remained stable. In fact, polyphenol levels remained stable for C treatment throughout boiling, resulting in the highest polyphenol content among all treatments. From the 30-minute mark onwards, a clear decreasing trend in polyphenol content was observed in all OH treatments (OH5, OH11 and OH26) continuing until the end of the boil (60 min). This is supported by statistically significant decreases in all three treatments ($p < 0.05$). That being said, OH treatments experienced significant reductions in their polyphenol content after peak concentrations were reached: OH5, OH11 and OH26 treatments decreased between 30 and 45 min; OH11 treatment repeated a significant decrease from 45 to 60 min. These results clearly demonstrate that the presence of electric fields contributes to significant polyphenol transformations in wort. Regarding this matter, it has already been described that during boiling, higher oligomeric phenolic compounds form complexes with proteins and the precipitate, while other small phenols (e.g. phenolic acids) can easily adsorb onto the hot trub.⁴⁷ The demonstrated effect of electric fields in decreasing the total polyphenol content throughout boiling might be related to these polyphenol-interaction mechanisms. The polyphenol behaviour observed in this study represents a noteworthy finding, suggesting that their levels in beer can be manipulated through the application of C or OH boiling methods. Considering the influence of brewing methods on the sensory and functional properties of beer, C boiling might enhance health benefits – especially in non-alcoholic beer – and improve flavour stability.⁴⁸ On the other hand, OH could be an interesting technology to explore when producing beer with reduced haze formation, lower astringency, and milder bitterness.⁴⁹

3.3 Volatile compounds

3.3.1 Essential oils assessment. Chromatographic analysis of volatile compounds present in the treated wort samples

identified five different essential oils: myrcene, linalool, caryophyllene, humulene and geraniol. Identification was based on their retention indexes and mass spectra, which were compared with those of reference compounds. The chromatogram displaying the peaks corresponding to each essential oil is provided in Fig. S1, while Fig. S2–S6 show the respective mass spectra.

As shown in Fig. 6, peak concentrations of all identified essential oils were reached within the first 20 min of boiling under all conditions, except for caryophyllene which peaked later in some cases. The most accentuated decreases in hop essential oil content were observed for myrcene, which was no longer detected after 40 min of boiling (Table S4), and for linalool, which experienced up to 81% loss of the content registered at the 20-minute mark (Table S5). These observations align with previous findings that link the low boiling point of these two essential oils with their rapid loss during boiling, when compared to the remaining hop essential oils identified in wort samples.⁵⁰ It is important to highlight that in the case of linalool, there is a clear tendency towards the progressive reduction in its concentration throughout boiling for the C treatment. OH treatments showed similar trends, with a more pronounced decrease as electric field intensities increased. At the 60-minute mark, OH5 showed statistical similarity with C boiling, confirming themselves as holding significantly higher linalool concentrations than boiling performed with higher electric field intensities (OH11 and OH26, respectively). With this said, for linalool, adding hops to a C boil or to an OH boil at 4–5 V cm⁻¹ seems to result in similar concentration levels (Table S5). Previous studies have shown that linalool levels in beers brewed with hop pellets during boiling tend to remain quite stable from the end of the boil to the finished beer.⁵¹ Based on this, it's reasonable to assume that the linalool concentrations measured at the end of boiling in this study would likely carry through to the final product in a similar way. According to Kaltner *et al.*,⁵² the flavour threshold for linalool in Pilsner-style beer is 5–10 µg L⁻¹. Given the levels observed at the end of boiling, both C (17.78 µg L⁻¹) and OH5 (23.56 µg L⁻¹) treatments are expected to contribute noticeably to the beer's floral and citrus-like aromas, often described as lavender, bergamot, or coriander-like.⁵³ In contrast, linalool levels in OH11 (9.93 µg L⁻¹) and OH26 (6.20 µg L⁻¹) treatments fall closer to or just above the threshold, suggesting they may have little to no detectable impact on the beer's sensory profile. As for myrcene, the absence of statistical significance ($p > 0.05$) and the pronounced decrease in concentration throughout boiling do not confirm any differences between C and OH processes (Table S4). As such, the addition of hops to a C boil or an OH boil, regardless of its electric field intensity, appears to lead to similar concentration levels. It is noteworthy that there is no survival of myrcene in the wort after 40 min of boiling, meaning that hop additions could benefit from being performed towards the end of boiling. However, even when hops are added at the end of boiling, on top of its rapid volatilization, myrcene can be oxidised, adsorbed to the non-polar surface of yeast cells and stripped from the fermenting beer by carbon dioxide.⁵⁴ For these reasons, myrcene's distinct "green hop aroma" in beer, often described as green, herbal and resinous can only be found



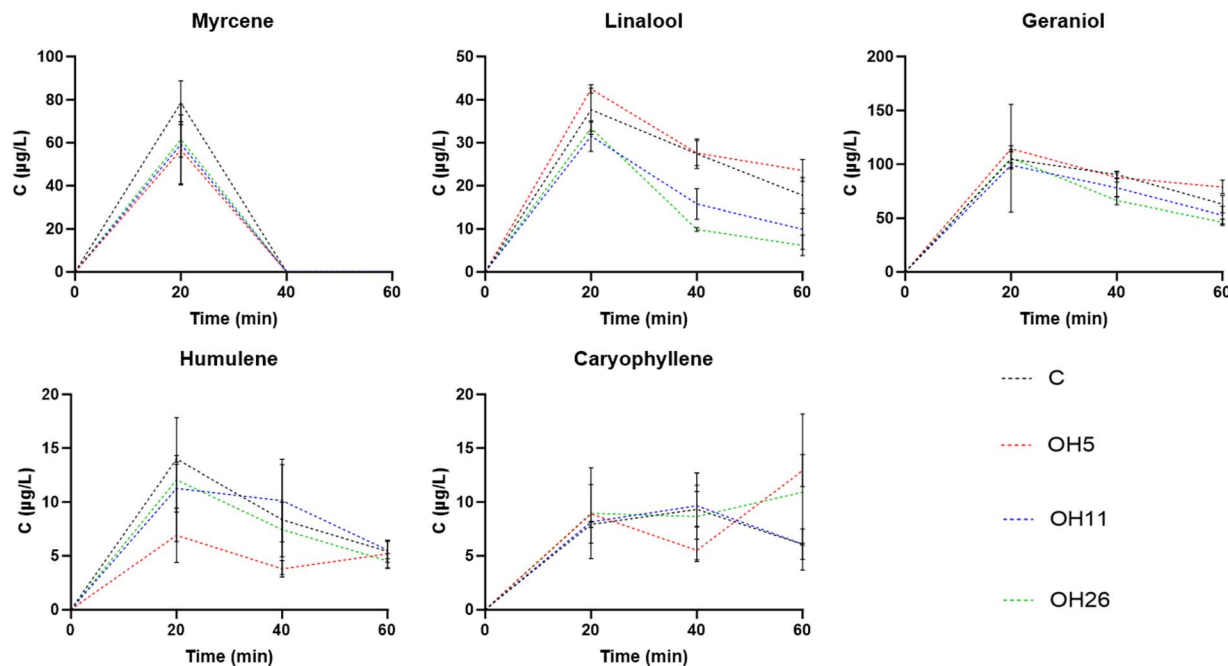


Fig. 6 Evolution of myrcene, linalool, caryophyllene, humulene and geraniol concentrations, expressed in 4-nonanol equivalents ($\mu\text{g L}^{-1}$), in wort samples, monitored at 20-minute intervals, over a 60-minute boiling period. Boils were performed through conventional (C) heating, in black, and ohmic heating (OH) methods using different electric field intensities: 4–5 V cm^{-1} (OH5) in red, 8–11 V cm^{-1} (OH11) in blue, and 22–26 V cm^{-1} (OH26) in green. Points represent mean values \pm standard deviation ($n = 3$), presented in Tables S4–S8.

in dry-hopped beers, where its aroma threshold (30–1000 $\mu\text{g L}^{-1}$) is attained.^{55–57}

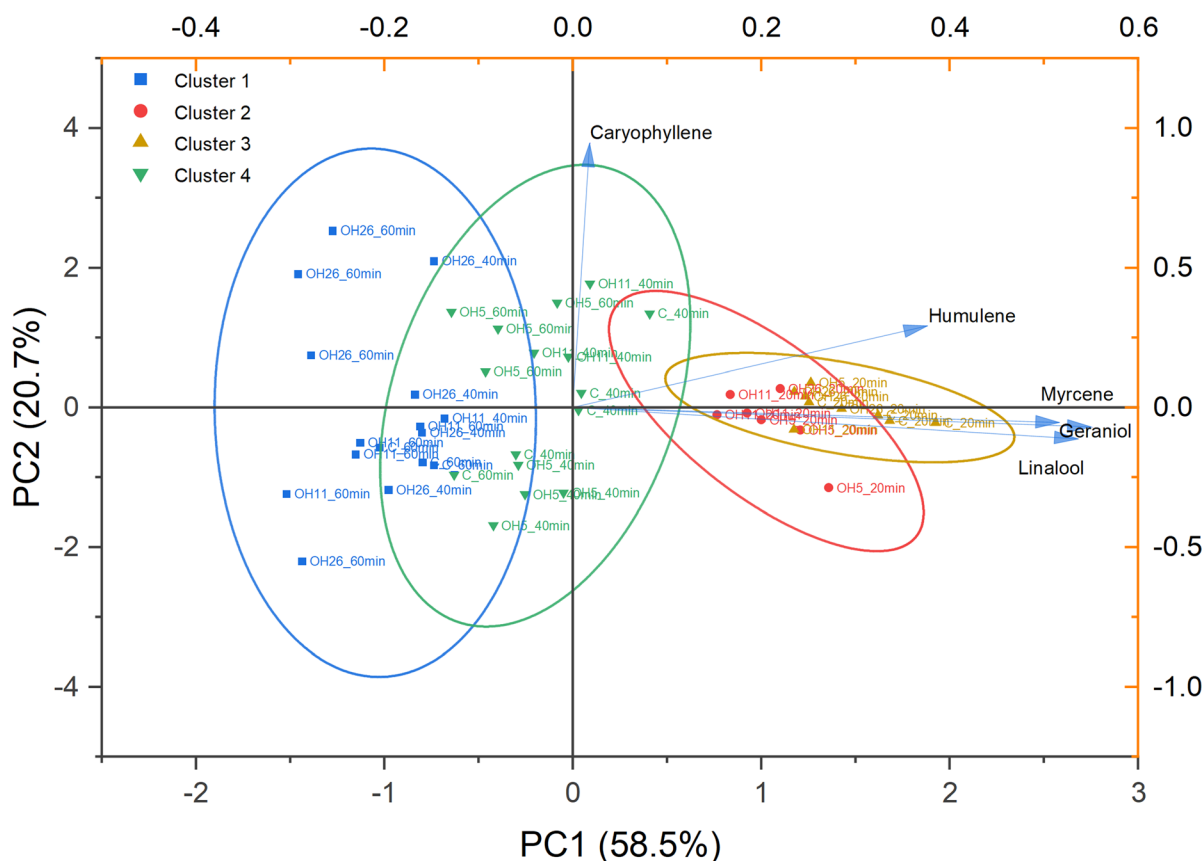
Geraniol, humulene and caryophyllene followed a more gentle and linear decrease when compared to the first group (myrcene and linalool), after the 20-minute mark. This aligns with the fact that essential oils featuring higher boiling points, are better preserved throughout wort boiling.⁵⁸ Among all the identified essential oils, geraniol stood out as having the highest concentration at the end of boiling (Table S8). Notably, it should also be mentioned that it had the highest concentration registered at the 20-minute mark. Geraniol behaved similarly to linalool, with OH treatments following the same trend as C boiling (see Fig. 6). OH5 and C retained significantly higher concentrations of geraniol than OH11 and OH26. This suggests that higher electric field intensities may lead to greater losses of this essential oil. Similarly to linalool, maximizing geraniol incorporation into wort may be achieved by adding hops later in the boil. If hops are boiled just for 20 min, the choice of boiling method among those tested appears to have little impact. Several studies have highlighted that during beer's fermentation, both ale and lager yeasts' metabolism converts geraniol to β -citronellol.^{59,60} Higher concentrations of geraniol in boiled wort are intimately linked with higher concentrations of β -citronellol in beer. Geraniol's biotransformation into β -citronellol occurs to a large extent; however, some precursor is still retained in beer.⁶¹ The presence of geraniol and β -citronellol above their flavour thresholds, 6 and 8 $\mu\text{g L}^{-1}$ respectively, could enhance their characteristic fruity, citrus and floral aromas in beer.^{61,62} Humulene exhibits a behaviour similar to that observed for linalool and geraniol under conditions C,

OH11, and OH26 (see Fig. 6); however, this trend is not observed for OH5. After 20 minutes, the humulene concentrations (Table S7) in the worts produced under C, OH11, and OH26 appear to be higher than those in OH5, although the differences are not statistically significant ($p > 0.05$). From this point onwards, humulene concentrations under the first three conditions tend to decrease, while in OH5 they remained stable until the end of boiling. Regardless of the variation pattern of humulene's concentration throughout boiling, all the treatments ultimately tend to converge to identical concentration values. Sesquiterpene hydrocarbons, such as humulene, are prone to oxidation during boiling and produce oxygenated sesquiterpenoids.⁶³ These oxygenated species, such as humulene epoxides and their derivatives, have already been linked to the woody/spicy hop flavour in beer.^{64,65} The oxidation products of humulene are described as being more soluble, stable and of lower flavour threshold in beer than humulene itself.^{66,67} This makes them more reliable to survive to the rest of brewing, impacting the beer's flavour and aroma. This can indicate that when hops are added to the last 20 min of boiling, OH5 treatment tends to a lower concentration of humulene, but to a higher presence of its oxygenated derivatives which can emphasize the woody and spicy character in beer. Additions made earlier in the boiling process tend not to reveal differences in the amount of humulene present in the wort produced under different electric field intensities. Regarding caryophyllene, all conditions appear to maintain a constant concentration between 20 and 40 min (Table S6). However, from 40 to 60 min, more unpredictable patterns emerged, hindering the extraction of definitive conclusions.



alone is just the first step to predict and control the sensory outcome, but additional integration with the full production process, along with the detailed analytical and sensory data are needed for a full comprehensive evaluation of this matter.

3.3.2 Multivariate analysis. Multivariate analysis techniques such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) can ease the interpretation of GC results of essential oils. They help identify patterns, correlations, and clusters within the dataset, making it easier to discriminate samples based on chemical composition. The PCA biplot, displayed in Fig. 7, provides a comprehensive overview of the relationships between different samples based on essential oil composition. PC1 (horizontal axis) explains 58.5% of the variance, while PC2 (vertical axis) accounts for 20.7%. Together, PC1 and PC2 capture approximately 79.2% of the total variance in the dataset. The distribution of samples within the plot reveals distinct clustering patterns, suggesting that different processing conditions influence the composition of essential oils in the extracts. Sample distribution within clusters is listed in Table S9. The blue cluster (cluster 1), positioned on the left side of the graph, consists of samples strongly associated with caryophyllene, indicating a negative correlation with PC1 and influence from PC2. In contrast, the red cluster (cluster 2),



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located on the right side, is highly influenced by humulene, with additional contribution from linalool and myrcene, suggesting a different chemical profile for these samples. The green cluster (cluster 4), centred near the origin, represents samples with intermediate characteristics, sharing some similarities with both the blue and red clusters, indicating a transitional chemical profile.

The loading vectors demonstrate that specific compounds play a major role in the separation of the different extracts, with caryophyllene influencing the left side and humulene, linalool, and myrcene contributing more to the right side of the biplot. Boiling time is also a significant factor in sample positioning. Samples boiled for 60 min tend to be located towards the left, while those boiled for shorter times (e.g., 20 min) are more aligned with the right side of the plot. This suggests that boiling time affects chemical composition. Longer boiling enhances caryophyllene extraction, while 20 and 40 min boils result in higher concentrations of myrcene, linalool, geraniol and humulene. Interestingly, OH samples boiled for 40 and 60 min (OH11 and OH26) presented higher concentrations of caryophyllene.

HCA (Fig. S7) also evidences that OH26 and OH5 samples fall into separate clusters, thus confirming that the intensity of the electric field applied leads to distinct chemical compositions, as observed for bitterness. Overall, multivariate analysis highlights the distinct essential oil profiles associated with different extracts. The clear differentiation between clusters suggests that specific parameters such as thermal load and electric field intensity can be adjusted to control the presence of key compounds, potentially optimizing the sensory attributes of the produced beer.

3.4 Sustainability assessment and industrial requirements

To evaluate the environmental performance of the thermal treatments applied in the boiling stage of brewing, sustainability metrics including the Environmental Factor (E-factor), Process Mass Intensity (PMI), and energy consumption were applied. The E-factor, PMI and energy consumption calculation are widely used and valuable metrics for assessing the environmental impact of chemical and technological processes, as they are fairly easy to generate and communicate informative measures of resource efficiency and waste generation.^{72,73} A summary of the evaluated green metrics for both C and OH boiling methods is presented in Table 1.

These indicators allow for a straightforward comparison of the greenness and efficiency of each heating method. In this context, ohmic heating (OH) presented optimal sustainability values. An E-factor close to 0 was achieved since hop debris

(90 mg of the initial 100 mg) had been the only waste generated throughout boiling. In turn, a PMI of nearly 1 has been calculated since beer's wort and hop pellets were the only required consumables for the process. In contrast, conventional heating, which relied on a thermostatically controlled water bath circulating hot water through the reactor jacket, showed significantly less favourable metrics. The E-factor for conventional heating was calculated to be 7.894, considering that besides the generated hop debris, approximately 0.25 L of water was lost through evaporation from the 4.35 L in the tank which has been used to feed the jacket. Furthermore, since the entire volume of circulating water was treated as a consumable input in the process, the PMI reached a value of 138.314. These findings underscore the lower water consumption and waste generation associated with ohmic heating, as has already been described in other studies which opposed ohmic and conventional heating methods.⁷⁴ This highlights OH technology's potential as a more sustainable alternative to conventional thermal technologies in brewing operations. Additionally, OH required an energy input of 0.13 kWh kg (calculated using data collected from voltage and current measurements during OH treatments). This corresponds to an energy efficiency of approximately 65%. This value was calculated by comparing the electrical energy supplied with the useful thermal energy estimated using the classical heat transfer equation ($Q = m \times cp \times \Delta T$). Assuming a wort density of 1.056 g mL⁻¹ and a specific heat capacity (cp) of 4191 J kg⁻¹ K⁻¹, the useful energy required to heat 30 mL of sample from 20 to 96 °C (ΔT) was estimated at 9.4 kJ (0.087 kWh kg⁻¹). OH systems are generally regarded as highly efficient, as they generate heat directly within the sample, minimizing thermal losses. Under ideal conditions, their efficiency can exceed 90%. However, in this case, the heating profile was intentionally designed to mimic the slower kinetics of conventional thermal systems, such as thermostatic baths and internally jacketed reactors. The heating process lasted approximately 320 seconds, during which heat dissipation to the surroundings – particularly through conduction *via* reactor components – became significant. Additionally, the applied electrical current was reduced to simulate slower heating, which resulted in less energy being delivered directly to the sample and increased heat losses. As such, the observed efficiency of 65% remains highly relevant given the simulated constraints.

In the conventional heating system, it was necessary to heat the water in the thermal bath to 98 °C. This hot water was then continuously circulated through the boiling jacketed glass reactor to promote indirect heating and raise the temperature of beer's wort from 20 to 96 °C. This method involved multiple heat transfer steps, resulting in significant thermal losses due to conduction through reactor walls and tubing, as well as losses to the surrounding environment. For comparison, maintaining the heating bath at 97 °C and using it to raise the wort temperature from 20 to 96 °C, consumed 0.3 kWh kg⁻¹. This value reflects the energy required to cycle the heating thermostat between "On" and "Off" while circulating water through the boiling reactor. This is more than twice the energy observed for OH and corresponds to an efficiency of only 29%. This estimation does not account for the energy required to initially heat

Table 1 E-factor, PMI, and energy consumption values for conventional and ohmic heating boiling methods

Method	E-factor	PMI	Energy input (kWh kg ⁻¹)
Conventional	7.894	138.314	0.300
Ohmic heating	28.409×10^{-4}	1.003	0.130



the water bath from 20 to 97 °C, which would significantly increase the total energy input of the conventional system.

These findings highlight the potential of OH technology as a more environmentally friendly alternative to conventional thermal technologies. By delivering energy directly into the product, OH systems can significantly reduce energy consumption and water usage, while also lowering thermal inertia and overall processing times. Even under constrained and less efficient conditions, as simulated in this study, OH demonstrated an interesting energy efficiency. However, scaling ohmic heating from laboratory to industrial-scale brewing applications requires careful validation of both technological and economic feasibility. Tools such as Life Cycle Assessment (LCA), Techno-Economic Analysis (TEA), and green assessment frameworks (e.g., AGREE, BAGI, RGB12) are recommended for future industrial projects to assess the broader impact and sustainability of the process.^{75–77} It is important to highlight that several industrial ohmic heating systems are already in operation for the continuous pasteurisation and sterilisation of food products, demonstrating the maturity and scalability of such technology in other sectors and unit operations. From a technological standpoint, adapting this setup to design a batch-scale boiling kettle suitable for brewing represents a relatively straightforward development. Moreover, OH systems operating at high-frequency regimes offer additional advantages, including reduced fouling due to the near absence of pronounced electrochemical reactions that could compromise the quality of the final product. These features collectively support the industrial scalability and practical application of OH in brewing. Nonetheless, pilot- and full-scale validation studies remain essential to confirm long-term reliability, energy performance, and integration feasibility within commercial brewing operations.

4 Conclusions

This study provides valuable insights into the impact that conventional (C) boiling and ohmic heating (OH) boiling, performed at different moderate electric field intensities, display in the extraction and behaviour patterns of key sensory-active compounds from hop pellets. Our findings reveal that electric fields have the potential to significantly influence the extraction dynamics and the final composition of beer, in ways that could transform brewing practices.

Data from this study demonstrate that OH methods accelerate bitterness development from the 15-minute mark onwards. Moreover, higher electric field intensities are correlated with higher wort bitterness. These findings offer brewers a promising way of reducing total boiling time or increasing the efficiency of the brewing process without compromising the bitterness of the brews. Moreover, a notable contrast between C and OH methods was observed for polyphenols. C boiling led to slower transformation kinetics of polyphenols, while OH boils accelerated this transformation process, ultimately leading to higher and lower polyphenol concentrations as boiling progresses, respectively. This dichotomy presents brewers with specific method advantages, depending on the desired product

characteristics, such as C boiling for brewing beer with enhanced health and flavour stability benefits, or OH boiling for beer products less prone to haze and astringency, with smoother bitterness profiles. Longer boiling periods reduce the levels of essential oils in beer, regardless of the chosen heating method. Myrcene and humulene retention do not seem to be influenced by the adopted heating method. However, for linalool and geraniol, higher electric field intensities (8–11 and 22–26 V cm^{−1}) result in more losses of these essential oils, while conventional and lower electric field intensity (4–5 V cm^{−1}) boils promote their retention in the final beer.

The contrasting effects highlighted in this study reveal the potential for brewers to strategically select heating methods and kinetics based on specific product goals and consumer preferences. Additionally, these findings encourage further research on common brewing practices where electric field processing and hop products may interact, such as late boil hopping, whirlpool hopping and dry-hopping towards advancing the brewing industry's continuous drive for innovation and excellence. The advantages of OH technology also align with broader goals of sustainable processing, where energy efficiency, resource optimisation, and environmental impact management are critical. Considering this, OH represents a promising green technology for future applications in thermal processing.

Author contributions

Gonalo Carvalho – writing the original draft, investigation, data curation, formal analysis, resources; Eduardo Coelho – writing the original draft, investigation, methodology, conceptualization; Rui M. Rodrigues – writing the original draft, conceptualization, methodology; Ant3nio A. Vicente – writing the original draft, conceptualization, supervision; Ricardo Nuno Pereira – writing the original draft, conceptualization, data curation, formal analysis, methodology, supervision.

Conflicts of interest

The authors state that they have no financial conflicts of interest or personal relationships that could have influenced the work presented in this paper.

Data availability

The data used to support the findings of this study have been included as part of the SI. See DOI: <https://doi.org/10.1039/d5fb00144g>.

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