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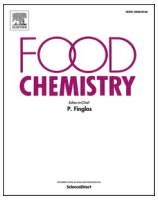

Quality evaluation of house cricket flour processed by electrohydrodynamic drying and pulsed electric fields treatment

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ABSTRACT

House crickets are expected to play a significant role in the future food sector. Electrohydrodynamic (EHD) drying offers an environmentally friendly alternative to conventional drying methods. Pulsed electric fields (PEF) is a non-thermal process that facilitates conventional processes. EHD was applied to house crickets with and without PEF pretreatment, and the effect of PEF and EHD on the quality of the insects was evaluated. PEF pretreatment positively affected the oven drying at 60 °C by reducing its duration and thus decreasing the energy consumption by 14.22%. Moisture removal of EHD was not sufficient to replace oven drying, but when combined with oven drying, the overall energy consumption was reduced by >50%. PEF processing also increased the protein solubility (53.07% higher than the respective control) and antioxidant activity (24.05% higher than the respective control) of the oven-dried samples and reduced the histamine content of the EHD-dried samples (25.87% lower than the respective control).

1. Introduction

The world population is rising and is expected to be almost 10 billion people by 2050, with a major increase in global food demand (Faostat, 2019). This abrupt change threatens our food security which requires appropriate actions such as replacing alternative food resources. Edible insects are one of the alternatives to address these issues as part of the future food systems. They provide a high nutritional composition (Rumpold and Schlüter, 2013) with a low environmental impact (Van Huis and Oonincx, 2017). House crickets, in particular, have been proposed, already, as food ingredients (Rossi et al., 2022), and are accepted in the EU as novel food (EFSA Panel on Nutrition et al., 2015).

Processing insects is essential for extending their self life and controlling their safety and quality. Drying is one of the major processes to extend their shelf life. Different drying methods are reported for processing edible insects, including oven drying, solar drying, freeze drying, vacuum drying, fluidized bed drying and microwave drying. Oven drying at temperatures between 50 and 80 °C is the most frequently applied method in the industry (Parniakov et al., 2021). The drying method is reported to affect product characteristics, like color, due to browning reactions and shrinkage, as well as the overall product quality (Parniakov et al., 2021). Additionally, drying has been reported to affect the histamine levels of some foods (Lin et al., 2014). Histamine is a chemical hazard, that can be found in insects (Chomchai and Chomchai, 2018), and its content has to be maintained below a certain limit.

Electrohydrodynamic (EHD) drying is a novel non-thermal drying method by which moisture is removed from the product mainly due to convection and partially electroporation. It consists of a high voltage power supply and repeated arrays of two electrodes (emitter and collector). Applying a high voltage difference between the electrodes ionizes the air around the emitter. The movement of these ions from the emitter towards the collector induces the so-called ionic wind. This ionic wind provokes convective dehydration on drying materials. EHD can be a promising alternative to conventional drying due to its scalability and significantly low energy consumption (Iranshahi et al., 2020).

Another novel food process that has promising potential for integration in the edible insect production is pulsed electric fields (PEF). PEF refers to the application of high voltage and short duration pulses to a

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food product that is placed between two electrodes. PEF processing causes cell disruption due to electroporation, which enhances the transport phenomena between the intracellular and extracellular environment of the material, accelerating conventional processes like drying (Raso et al., 2016). Furthermore, PEF has been reported to enhance the quality of foods, while being appropriate for processing insects, enhancing conventional drying, and extracting nutrients (Shorstkii, 2022; Psarianos et al., 2022).

The present study explores the applicability of EHD drying and PEF pretreatment on house crickets to reduce the drying time and positively affect the quality of the final product.

2. Materials and methods

Living house crickets (*Acheta domestica*) were purchased from Tropic Shop (Nordhorn, Germany) and were inactivated by freezing at −20 °C and then thawed at 25 °C for 2 h and used for further experiments. All chemicals were purchased from Carl Roth Gmbh & Co. Kg (Karlsruhe, Germany), unless stated otherwise. The moisture content of the samples was estimated by measuring the weight difference after placing them at 105 °C for 48 h and was equal to 72.05 ± 0.98 g/100 g of crickets.

2.1. Pulsed electric field (PEF) treatment

Whole fresh insects (25 g) were mixed with 100 ml of water, placed inside a batch chamber with a 40-mm electrode distance and processed with an HVP-5 (DIL, Quackenbrück, Germany) PEF system. The system was connected to an oscilloscope (Voltcraft, DSO-1062D, Conrad electronics, Hirschau Germany) that was used to monitor the pulses. The picture of the pulse is presented in the supplementary material (Fig. S1). The oscilloscope had two channels, one that corresponded to the voltage and one that corresponded to the current. The insects were treated with 500 almost rectangular pulses with pulse width of 25 μs at the following conditions: 4.4 kV/cm, 41.6 A, 20 Hz and a temperature that did not exceed 25 °C after the treatment. The specific energy input was calculated using Eq. (1) (Raso et al., 2016)

$$w_{spec.}(kJ/kg) = n/m\hat{A}\cdot\int_0^{\infty} V(t)\bullet I(t)dt \quad (1)$$

where n is the number of pulses, m (kg) is the mass of the sample, V(t) and I(t) are the voltage and the current as a function of the treatment time, and t (s) is the time. Afterwards, the samples were sieved and blotted with a paper towel to remove excess water. Untreated samples were placed inside water at the same ratio for the whole treatment to make samples comparable.

2.2. Drying process

2.2.1. Oven drying

The whole fresh insects were placed inside a conventional oven dryer and were spread in a monolayer in drying trays of 30 cm × 30 cm. The crickets were dried at a constant temperature of 60 °C and an average air velocity of 1 m/s. The weight of each tray was recorded at different time intervals until equilibrium was reached. The total energy consumption was measured using the MegaPower™ Plug Power Meter (Digiparts, Canada).

2.2.2. Electrohydrodynamic (EHD) drying

The set-up of the EHD drying was based on the work of (Iranshahi et al., 2020) and took place inside a lab-scale chamber of 40 × 40 × 70 cm. The set-up consisted of an emitter electrode connected to a positive high voltage power supply and a collector electrode connected to a negative high voltage power supply. The insects were placed on the plate collector (30 cm × 30 cm). A multimeter (Keysight U1253B, Santa Rosa, CA, USA) and a 1000:1 high voltage probe (Testec HVP-40, Testec Elektronik GmbH, Germany) were used to measure the discharge energy consumption, while a MegaPower™ Plug Power Meter (Digiparts, Canada) was used to measure the total energy consumption. The drying set-up was connected to a digital scale (PG5001-S, Mettler-Toledo, Greifensee, Switzerland) to measure the weight difference directly during the drying process. The insects were dried for 580 min to ensure equilibrium was reached. The energy consumption E (J) was calculated by multiplying discharge voltage V (V), current I (A) and drying time t (s):

$$E = V\hat{A}\cdot I\hat{A}\cdot t \quad (2)$$

2.2.3. Drying curves

For both oven and EHD drying methods, the moisture load M_t was calculated for every time interval t as $M_t = (m_t\text{-}m_s)/m_s$, where m_t (g) and m_s (g) are the mass of the sample at time t and after being completely dried, respectively. Afterwards, the moisture ratio (MR) was calculated as $MR = (M_t\text{-}M_e)/(M_0\text{-}M_e)$, where M_t, M_e and M_0 are the moisture load of the samples at each time interval t, at equilibrium and at the beginning of the process (t = 0 min), respectively. To minimize errors caused by fluctuation, it was considered that $M_e = 0$ (Ostermeier et al., 2018). The moisture ratio was expressed as a function of drying time t (min) with the models that are presented on Table 1.

The models were evaluated based on the correlation coefficient R^2, the reduced χ^2 (Eq. (2)) and the root mean square error RMSE (Eq. (3)):

$$\chi^2 = \frac{\sum_{i=0}^{N}(MR_{i,p} - MR_{i,e})^2}{N - n} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=0}^{N}(MR_{i,p} - MR_{i,e})^2}{N}} \quad (3)$$

where $MR_{i,p}$ and $MR_{i,e}$ are the calculated and experimental values of the MR, N is the number of observations and n is the number of parameters of the model. Higher values of the R^2 (close to 1) and lower values of χ^2 and RMSE indicate a better fitting of the model to the experimental data. The regression analysis was performed with IBM SPSS Statistics 23 (IBM Corp., Armonk, N.Y., USA).

2.3. Product quality

Prior to each analysis, the insects were dried with a laboratory Retsch mill (Retsch Grindomix, Retsch GmbH, Germany) to become a homogenous material. Afterwards the milled samples were stored at room temperature in order to be further evaluated. All quality parameters were measured within two weeks.

2.3.1. Bulk density

Bulk density was estimated gravimetrically by placing the samples in a volumetric cylinder of a known volume and measuring the weight. The results are expressed as (g/cm^3).

Table 1
Models used to express the MR as a function of time. k corresponds to the drying rate (1/s), a and b are coefficients of the equations, n is an exponent and t is the drying time (min).

Model name	Equation	Reference
Newton	$MR = e^{-k\bullet t}$	(Demir et al., 2004)
Page	$MR = e^{-k\bullet t^n}$	(Sarimeseli, 2011)
Henderson and Pabis	$MR = a\hat{A}\cdot e^{-k\bullet t}$	(Rahman et al., 1997)
Logarithmic	$MR = a\hat{A}\cdot e^{-k\bullet t} + b$	(Sarimeseli, 2011)
Medilli	$MR = e^{-k\bullet t^n} + b\hat{A}\cdot t$	(Midilli et al., 2002)
Wand and Singh	$MR = 1 + a\cdot t + b\cdot t^2$	(Wang and Singh, 1978)

2.3.2. Color

Color was measured with a Minolta chroma meter (CM-2600D, Konica Minolta Inc., Japan) with CIELab system, illuminant D_{65} (daylight), SCE (specular component excluded) mode, and 10° observer angle. The colorimeter was calibrated with standard white plate prior to the analysis.

The overall color change, ΔE was estimated with Eq. (4):

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (4)$$

where L^*, a^*, and b^* correspond to the color coordinate system parameters of the CIELAB system. L^* corresponds to the light–dark spectrum (0 (black) to 100 (white)),a^* corresponds to the red-green spectrum (−60 (green) to 60 (red)) and b^* corresponds to the yellow–blue spectrum ranging from (−60 (blue) to 60 (yellow)) of the samples. Color was measured for insects samples before (L_0^*, a_0^*, and b_0^*) and after drying (L^*, a^*, and b^*).

2.3.3. Total phenolic content (TPC)

An amount of 0.5 g of samples was homogenized with 12 ml of a ethanol/acetic acid/water solvent (50:8:42) for 1 h and then samples were centrifuged at 3900 χg for 10 min and the supernatant was collected (Bolat et al., 2021). The TPC of the extract was measured with the Folin-Ciocalteau method by mixing 0.1 ml of extract with 7.9 ml of water, 0.5 ml of the Folin reagent (1 N) and 1.5 ml of a saturated Na_2CO_3 solution and incubating the mixture for 30 min at 40 °C in the dark. Then the absorbance was measured at 765 nm. Gallic acid was used for the calibration curve (100–1000 mg/L) and the results were expressed as g gallic acid equivalent (GAE)/ 100 g.

2.3.4. Antioxidant activity

The obtained extract from the crickets that was described in Section 2.3.3 was used for estimating the antioxidant activity.

2.3.4.1. Free radical scavenging activity (DPPH). The free radical scavenging activity was estimated by mixing 0.1 ml of extract with 3.9 ml of a freshly prepared DPPH solution at $6{\cdot}10^{-5}$ M and incubating in the dark at room temperature for 15 min. Then, the absorbance of the mixture was measured at 515 nm against a blank that contained methanol instead of sample extract. Trolox was used for the calibration curve (0.1–1 mM) and results were expressed as g trolox equivalent (TE)/100 g (Brand-Williams et al., 1995).

2.3.4.2. Ferric reducing iron power (FRAP). FRAP was measured by mixing 0.5 ml of extract with 0.5 ml solium phosphate buffer (0.2 M, pH = 6.6) and 0.5 ml of potassium ferricyanide 1%.and incubating at 50 °C for 20 min. Afterwards, 0.5 ml of TCA 10% were added, followed by the addition of 2 ml water and 0.4 ml of ferric chloride 0.1%. The absorbance of the mixture was measured at 700 nm after vortexing. Trolox was used for the calibration curve (50–500 μM) and the results were expressed as g TE/100 g (Jakovljevic et al., 2014).

2.3.4.3. Cheletating ability. Chelating ability was estimated by mixing 0.1 ml of extract with 3.7 ml methanol and 0.1 ml of 2 mM solution of ferrous chloride, incubating the mixture at room temperature for 3 min and then adding 0.2 ml of a 5 mM ferrozine solution. The mixture was incubated at room temperature for 10 min and then the absorbance was measured at 562 nm. EDTA was used for the calibration curve (0.25–2 mg/ml) and the results were expressed as g EDTA equivalent/100 g (Dinis et al., 1994).

2.3.5. Protein solubility

To estimate protein solubility, 0.5 g of samples were homogenized with 10 ml of water at room temperature for 1 h and then the mixture was centrifuged at 3900g for 10 min. Protein content was measured in the supernatant with the Lowry method (Bolat et al., 2021). Bovine serum albumin was used for the calibration curve (40–300 μg/ml) and the results were expressed as g protein/100 sample.

2.3.6. Maillard reaction

The progress of Maillard reaction was measured by measuring the concentration of hydroxylmethylfulfural (HMF). Briefly, 2 ml of the supernatant that was obtained from the process described in section 2.3.3 was mixed with 2 ml of a 12% TCA solution and 2 ml of a 25 mM TBA solution. The mixture was incubated at 40 °C for 50 min and then the absorbance was measured at 443 nm (Cohen et al., 1998). Standard HMF was used for the calibration curve (0.4–25 mg/ml) and results were expressed as g HMF/100 g.

2.3.7. Polyphenoloxidase (PPO) activity

For measuring the PPO activity, 0.2 ml of sample was homogenized with 5 ml of 0.1 M sodium phosphate buffer (pH of 6.5) for 60 min at room temperature. Then, they were centrifuged at 3900g for 20 min at 8 °C. Afterwards, the PPO activity was measured by mixing 2.25 ml of reaction buffer (0.5 mM of SDS in 0.1 M sodium phosphate buffer) with 0.15 ml of the supernatant 0.3 ml of a 0.5 M proline solution and 0.3 ml of a catechol solution (2.2 mg/ml in reaction buffer). The absorption of the mixture was measured every 30 s, for 10 min and the PPO activity was calculated from the slope of the curve of the absorption and time (Reinkensmeier et al., 2016).

2.3.8. Histamine concentration

Histamine was extracted from the samples by mixing 2 g with 20 ml of a 0.85% NaCl solution for 2 min. Then the mixture was centrifuged at 3900g for 10 min at 4 °C and the supernatant was collected, diluted 1:2 with the saline solution and then mixed with 0.5 g of a salt mixture (6.25 g sodium sulfate and 1 g trisodium phosphate monohydrate). Then 2 ml of butanol were added, the mixtures were mixed for 1 min and then centrifuged at 3900g for 10 min. The upper layer is collected, evaporated and solubilized with 1 ml of water. Then 5 ml of a 1.1% sodium carbonate solution and 2 ml of the reaction reagent were added. Mixtures were incubated at room temperature for 5 min and the absorption was measured at 496 nm. The reaction reagent was prepared by mixing 1.5 ml of a 0.9% sulfanilic acid solution in 4% HCl with 1.5 ml of a 5% $NaNO_2$ solution inside an ice bath. After 5 min, another 6 ml of the $NaNO_2$ solution was added and after 5 min 41 ml of water was added (Patange et al., 2005). Standard histamine (Merck, Darmstadt, Germany) was used for the calibration curve (5–50 μg/ml) and results were expressed as mg histamine/100 g.

2.3.9. Volatile profile

The volatile profile was measured using a GC–MS coupled with a solid phase microextraction (GC–MS-SPME) technique, according to (Rossi et al., 2021). Briefly, samples were placed inside a vial and preheated at 45 °C for 10 min.Then, a fiber (SPME Carboxen/ PDMS, 85 μm, Stalleflex Supelco, Bellefonte, PA, USA) was positioned inside the vial to absorbe the volatile molecules for 40 min. Volatiles were desorbed in the injector of a gas-chromatograph for 10 min and separated through a column Chrompack CP-Wax 52 CB (Chrompack, Middelburg, Olanda) with a length of 50 m and internal diameter of 0.32 mm. The analysis was performed using an Agilent Technology 7890A gas chromatograph, Network GC System combined with a Network Mass Selective detector HP 5975C mass spectrometer (Agilent Technologies, Palo Alto, CA, USA). The volatile peaks were identified via comparison of mass spectral data of molecules from the NIST library (NIST/EPA/NIH Mass spectral Library, Version 1.6, United States of America) of 2011 and WILEY (sixth edition, United States of America) of 1995. 4-methyl-2-pentanol at 10.000 mg/kg was used as standard at a concentration of 20 mg/kg for each sample.

2.4. Statistical analysis

All processing pathways were repeated twice and each analytical method was repeated in triplicate (n = 6). Statistical differences among means of data obtained for samples that were subjected to different processing pathways are explored with an one-way analysis of variance (ANOVA) at a significance level of 0.05, with Duncan's test applied post hoc to separate means. Data that did not follow a normal distribution were normalized prior to the analysis. Principal component analysis (PCA) was performed using Statistica software (version 8.0; StatSoft., Tulsa, OK) on raw data to highlight the statistical variance among the volatile profiles.

3. Results and discussion

3.1. Drying curves

According to the drying curves (Fig. 1), PEF has a significant effect on the drying of the crickets. The oven-dried insects that were subjected to PEF treatment showed a lower moisture ratio throughout the whole drying process. Additionally, the drying time was reduced with PEF. The oven-dried untreated samples reached a drying equilibrium at 180 min of drying, while the PEF treated ones at 150 min of drying. Regarding the application of PEF alone as a pretreatment for the drying of crickets to produce cricket flour, it is hypothesized that due to PEF-induced electroporation, the moisture removal from the crickets was enhanced, leading to a lower moisture content and moisture ratio in the final product.

However, EHD drying was not sufficient, for both untreated and PEF-treated samples. For both samples, EHD drying reached equilibrium at 210 min, when the water content of the insects was not reducing further. The insufficiency of EHD drying for insects could be attributed to the low temperature of the drying (EHD operates at room temperature ≈25 °C). Preliminary tests were performed with oven drying of insects at 30 °C, which similarly showed that low-temperature convective drying could not dry the insects to a moisture of <5% (data not shown), which is shown to be sufficient for avoiding spoilage (Kamau et al., 2018). Furthermore, the positive effect of PEF on the drying kinetic was not observed for the EHD-dried samples.

The drying curves of house crickets at 60–80 °C have been reported to show a rapid reduction in the first 60 min of the oven drying and reach equilibrium after 360 min (Bawa et al., 2020). In the present study the rapid reduction of the drying curve in the first 60 min of drying was observed as well for the oven dried samples. However, the equilibrium was reached faster in the case of the present study, which could be attributed to the low initial amount of sample that was 25 g in compare to the study of Bawa et al. (2020), who reported the longer drying time for 200 g of crickets until constant weight (Bawa et al., 2020). The loading density of the tray during the oven drying can reduce the drying rate, as shown for okra (Emmanuel and Fakayode, 2011). The oven drying of house crickets in a single-layer position of crickets has been reported to be faster than the multi-layer setting at the same temperature (Fröhling et al., 2020). However, the oven drying settings of house crickets can differ, as for instance in the case of Khatun et al. (2021), who reported 20 h of drying at 65 °C of a thick layer of crickets (Khatun et al., 2021).

The application of PEF treatment has been widely reported to improve the drying rate of foods and accelerate the drying process due to an increased vapor transfer between the intracellular and extracellular environment of foods. This could lead to a reduction of the energy consumption of the drying process (Punthi et al., 2022). This effect has been reported for various food materials, e.g. potatoes (Lebovka et al., 2007), apples (Wiktor, 2013) and onions (Ostermeier et al., 2018). The positive effect of PEF on the drying kinetics has been reported for edible insects, as well. PEF pretreatment has been shown to increase the drying rate of oven drying of black soldier fly larvae (Shorstkii, 2022; Alles et al., 2020), as well as the drying rate of freeze drying and infrared drying of black soldier fly and yellow mealworm larvae (Bogusz et al., 2023,2022; El Hajj et al., 2023). Therefore, the positive effect of PEF pretreatment on the drying kinetic of house crickets was somewhat expected.

Regarding EHD drying, the present study is the first one to report its application on edible insects. It has been applied successfully on plant materials, such as slices of apples (Hashinaga et al., 1999) and carrots (Ding et al., 2015). Additionally, EHD drying has been combined with a PEF pretreatment in the case of apple slices, with the PEF treatment leading to a 39% reduction of the drying time (Iranshahi et al., 2023). However, in the case of house crickets EHD drying alone was not efficient in drying the crickets, while no effect of the PEF pretreatment was observed for the samples subjected to EHD drying.

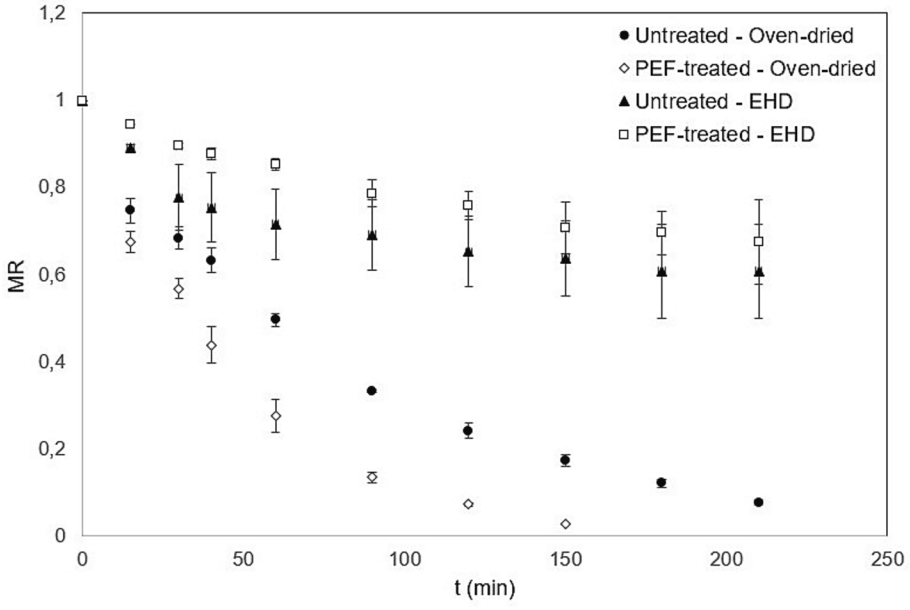

Fig. 1. Moisture ratio (MR) of samples during the drying process. Error bars represent the standard error of means of the MR that was obtained from different replications of the same process.

Drying of insects is facilitated as temperature increases (Shorstkii, 2022). Milder temperatures would cause a partial protein denaturation, induced by heating or oxidation, even at 40 °C, which would affect surface hydrophobicity and thus protein complexes (Shorstkii, 2022; Chelh et al., 2006). This increase of protein hydrophobicity could lead to alignment of the proteins at the water/oil interface and, depending on the amino acid sequence and degree of denaturation, cause a steric hindrance due to the generation of protein parts that extend from the lipid to the water fraction (Damodaran, 2005; Timilsena, 2016). Therefore, the driving force of moisture removal from insects has been reported to be stronger and the effect of PEF treatment more evident at higher temperatures (Shorstkii, 2022).

When the EHD drying reached equilibrium and the moisture removal would not progress further, the samples were not considered dried. Therefore, after the EHD drying, they were placed in a drying oven at 60 °C for 1 h, at the same conditions described in Section 2.2.1, so that they were properly dried. The final moisture content that was targeted for the samples was <5%, which according to the moisture absorption isotherm for house crickets at 25 °C would correspond to a water activity $a_w < 0.4$ (Kamau et al., 2018). The EHD drying was considered sufficient for the insects when combined with a short oven drying treatment, similarly shown for mushrooms (Taghian Dinani, 2014). The combination of the two drying methods stemmed from the fact that EHD drying is recognized for its significantly lower energy consumption compared to other drying techniques. Consequently, by merging these methods, it was anticipated that a dry end product could be achieved with even lower energy consumption. Moreover, EHD is a low-temperature drying method which can lead to higher product quality by preserving heat-sensitive compounds (Iranshahi et al., 2023).

These samples were considered for further characterization and compared to the samples that were subjected to only oven-drying, with and without a PEF treatment. The drying processes that were evaluated for their effect on the insect matrices were oven-drying and EHD-drying followed by a shorter oven-drying step. The effect of PEF treatment on the insects when combined with both drying pathways, was considered as well.

Table 2
Evaluation of models applied to the drying curves of samples subjected to different processing pathways.

Model		Untreated Oven-dried	PEF treated Oven-dried	Untreated EHD-dried	PEF treated EHD-dried
Newton	R^2	0.990	0.994	0.564	0.927
	χ^2	0.1807	0.1266	0.2903	0.3107
	RMSE	0.4033	0.3355	0.5112	0.5288
Page	R^2	0.993	0.994	0.975	0.994
	χ^2	0.0008	0.0007	0.0005	0.0001
	RMSE	0.0252	0.0240	0.0193	0.0089
Henderson and Pabis	R^2	0.993	0.995	0.809	0.965
	χ^2	0.0009	0.0007	0.2682	0.3585
	RMSE	0.0267	0.0239	0.4632	0.5355
Logarithmic	R^2	0.993	0.996	0.984	0.995
	χ^2	0.0011	0.0007	0.0003	0.0001
	RMSE	0.0275	0.0218	0.0154	0.0088
Midilli	R^2	0.994	0.873	0.827	0.959
	χ^2	0.1753	0.2120	0.1697	0.1700
	RMSE	0.3243	0.3432	0.3191	0.3194
Wand and Singh	R^2	0.997	0.966	0.880	0.990
	χ^2	0.0029	0.0055	0.0034	0.0001
	RMSE	0.0482	0.0619	0.0519	0.0108

Table 2 shows the applicability of the models to the drying curves of the samples. The application of these models is essential to increase the predictability of the processes (Wiktor, 2013). Even though EHD drying was insufficient to dry the insects completely, the models that showed a good fitting to the experimental data were applicable to both drying methods and for PEF-treated and untreated samples. The ones that had a good fitting for all samples were the Page model and the Logarithmic model with $R^2 > 0.97$ for all samples and χ^2 and RMSE being <0.001 and <0.1, respectively. The other models were considered inappropriate due to low values of R^2 or high values of χ^2.

3.2. Product quality

Table 3 shows the evaluated key indicators of the product quality of the insects. The bulk densities of the EHD-dried samples were significantly ($p < 0.05$) higher than the one of the oven-dried samples due to a higher amount of remaining water in the material. The overall color difference of the EHD-dried samples was significantly ($p < 0.05$) higher than the oven-dried ones. Similarly, the L^* values of the oven-dried samples were higher. One reason for the color difference could be the Maillard reaction, but the EHD-dried samples showed a significantly lower HMF content ($p < 0.05$), while PEF not affecting the HMF levels. Another reason could be the browning enzymatic activity. However, no PPO activity was observed in the samples. Finally, the color differences could be explained due to oxidative reactions in the sample, which were also confirmed by the volatile profile.

EHD drying did not affect the TPC or the antioxidant activity ($p > 0.05$). However, PEF treatment did increase the free radical scavenging activity and the ferric iron reducing power of the oven-dried samples by 22.90% and 24.05%, respectively. However, this positive effect was not transferred to the EHD-dried insects, which showed no significant differences due to the PEF treatment ($p > 0.05$). Since there are no differences in the TPC ($p > 0.05$), the differences in antioxidant activity were attributed to antioxidant peptides, which have been reported to increase their antioxidant activity and show changes in their properties due to PEF processing (Lin et al., 2017).

The effect of PEF on proteins was observed due to the significant (p

Table 3
Key indicators of the quality of the insects obtained from each processing pathway. Values are presented as mean ± standard deviation (SD). Results are expressed g/100 g wet matter. Superscript letters (a,b,c, and, d) indicate significant differences ($p < 0.05$) among the means of values obtained from replicates of the same measurement ($n = 6$).

	Untreated Oven-dried	PEF treated Oven-dried	Untreated EHD-dried	PEF treated EHD-dried
Bulk density (g/cm^3)	245.56 ± 17.60^a	257.78 ± 15.59^a	303.33 ± 9.19^b	322.22 ± 13.77^c
△E	12.86 ± 1.83^a	10.27 ± 1.22^b	20.56 ± 1.35^c	15.31 ± 1.60^d
TPC (g GAE/100 g)	0.91 ± 0.09^a	0.98 ± 0.18^a	1.00 ± 0.06^a	0.98 ± 0.06^a
Free radical scavenging activity (g TE/100 g)	0.83 ± 0.08^a	1.02 ± 0.15^b	0.95 ± 0.10^{ab}	0.91 ± 0.16^{ab}
FRAP (g TE/100 g)	0.79 ± 0.04^a	0.98 ± 0.10^b	1.16 ± 0.25^c	0.99 ± 0.06^{bc}
Chelating ability (g EDTA equivalent/100 g)	2.75 ± 0.24^a	2.79 ± 0.23^a	2.63 ± 0.18^a	2.29 ± 0.26^b
Protein solubility (g protein/100 g)	5.71 ± 0.47^a	8.74 ± 0.44^b	4.20 ± 0.26^c	3.41 ± 0.78^d
HMF (g HMF/100 g)	3.93 ± 0.66^a	3.97 ± 0.49^a	1.95 ± 0.37^b	2.46 ± 0.46^b
Histamine (mg/100 g)	89.09 ± 18.58^a	90.39 ± 10.52^a	127.27 ± 17.49^b	94.35 ± 5.83^a

< 0.05) increase in the protein solubility from the oven-dried samples (53.07% increase in compare to the control). This increase in solubility could also be attributed to an enhancement of extractability because PEF can enhance the extraction of insect proteins due to electroporation (Psarianos et al., 2022). However, protein solubility was significantly ($p < 0.05$) lower for EHD-dried samples than for oven-dried samples. The EHD-dried samples were subjected to both drying processes and for a longer time, which would cause a higher surface hydrophobicity due to denaturation (Chelh et al., 2006), thus reducing solubility.

Regarding the histamine content, there were no significant differences between the oven-dried samples and the PEF-treated EHD-dried one ($p > 0.05$), but the untreated EHD-dried sample had a significantly higher histamine content ($p < 0.05$). Histamine is produced from histidine due to a reaction with the enzyme histidine decarboxylase that can be produced by bacteria (Epps, 1945). PEF processing and thermal treatment have been reported to reduce enzymatic activity (Huang et al., 2012). However, the lack of PEF treatment and the mild temperature levels of the EHD-dried sample could be responsible for a higher enzymatic activity of histidine decarboxylase. Even though this sample was oven-dried for 1 h, after the EHD drying, it is possible that the histamine was already formed before the sample was subjected to a higher temperature.

From the analysis of the volatile profile of the samples, there were 56 identified molecules belonging to different classes of compounds, including aldehydes, ketones, alcohols, acids, esters, alkanes and pyrazines. Compounds are presented as supplementary material (Table S1).

According to the obtained results, EHD-dried samples, with or without PEF pretreatment, had a higher concentration of volatile compounds than the oven-dried ones. In particular, EHD samples were characterized by a higher amount of acids and pyrazines while oven-dried samples showed the same trend but in lower amounts. Acids reached concentrations of 172.22 ± 10.55 mg/kg and 124.78 ± 28.57 mg/kg in the untreated and PEF-treated EHD-dried samples, respectively, while lower level were measured in oven-dried samples without and with PEF (54.74 ± 1.80 mg/kg and 42.42 ± 3.73 mg/kg, respectively). Acetic acid was the most abundant acid followed by short chain fatty acids.

Pyrazines were the second most abundant class of volatiles reaching amounts of 49.45 ± 7.83 mg/kg and 87.41 ± 46.04 mg/kg in the non-treated and PEF-treated EHD-dried samples, respectively, and 16.21 ± 3.77 mg/kg and 18.26 ± 0.89 mg/kg in the non-treated and PEF-treated oven-dried samples, respectively. The presence of pyrazines in crickets has been reported (Rossi et al., 2021) and was expected since animals use them as attractive or deterrent compounds, depending on the situation (Müller and Rappert, 2010). Although heating and cooking are the main cause of pyrazine formation, their amount in oven-dried samples was lower. This could be explained by pyrazine low vapour pressure and evaporation process that could have reduced their content.

To highlight differences among samples, PCA analysis was carried out on raw data obtained from the analysis of the volatile molecule. Fig. 2 a and b represent the projections of the samples and variables in the spaces contained by the two main components PC1 and PC2, which account for 46.12 % and 32.35 %, respectively, of the total variance among the different samples. Independently from the treatment, oven-dried samples clustered together in the right side of the factorial space and were separated from the EHD-dried samples along the PC1. Instead, EHD-dried samples were separated based on the PEF treatment along PC2. The projection of variables on factor planes showed that different volatile molecules affected the grouping of samples along PC1 and PC2. In fact, most of the pyrazines were found in the PEF-treated EHD-dried samples, while short-chain fatty acids (including Propanoic acid, Butanoic acid, Hexanoic acid, Heptanoic acid and Butanoic acid, 3-methyl-) were found in both EHD-dried samples. The major volatile molecules in oven-dried samples were aldehydes and ketones, such as Pentanal, Hexanal, Propanal, 2-methyl-, 1-Octen-3-one, and 3-Penten-2-one, 4-methyl-. These molecules may be the result of lipid oxidation and fatty acid degradation (Xia and Budge, 2017).

3.3. Energy consumption

The energy requirements of all processing pathways are a summary of the energy requirements of each process separately. The specific energy consumption (*SEC*) of the PEF treatment was 40.21 kJ/kg and the energy that was required for the sample that was subjected to the treatment was 5.03 kJ. For the oven drying and the EHD drying, the power usage was 604 and 12.7 W, respectively. Even though the EHD drying reached equilibrium at approximately 210 min (experimental data), the EHD drying was performed for a maximum of 580 min for all samples. Therefore, the 580 min were considered for the calculation of the energy and not the 210 min (Fig. 3). PEF treatment was able to reduce the energy consumption by 14.22% due to a reduction in the drying time (from 305,928 to 262,425 kJ/kg). However, the processing pathway that includes EHD drying, with and without implementing PEF processing (105,086 and 105,287 kJ/kg, respectively), required less than half of the energy that was consumed for conventional oven drying. Therefore, even though EHD drying by itself was not sufficient to replace oven drying, it can be implemented as an intermediate step to reduce the oven drying time and therefore significantly reduce energy requirements.

Apart from the low energy requirement, EHD drying has been shown to be much more cost-effective than conventional oven drying, when investment cost, cost of drying per kg dried material, payback period and net present value are considered (Iranshahi et al., 2023). PEF has been characterized, also, by cost-efficiency due to its low energy costs and high efficiency as a pretreatment. It poses, however, the drawback of the high setup cost (Ghoshal, 2023; Toepfl and Knorr, 2006).

4. Conclusions

The applicability of EHD drying was tested on house crickets and PEF was used as a pretreatment to facilitate the drying process and enhance the product quality. PEF treatment, when combined with conventional oven drying, could reduce the energy consumption of the process and improve product quality, e.g. antioxidant activity and protein solubility. EHD drying be implemented as an intermediate drying step that would reduce the oven drying to 1 h, with a major decrease in energy consumption and a retention of higher amount of volatile molecules. When the EHD/oven drying processing pathway was combined with PEF processing, there was a further positive effect on product quality due to the reduction of the histamine content. The present study underlines the potential of EHD drying and PEF processing in edible insect production with possible industrial applications due to the higher scale applicability of both processes.

CRediT authorship contribution statement

Marios Psarianos: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **Kamran Iranshahi:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing. **Samantha Rossi:** Investigation, Methodology, Validation, Visualization, Writing – review & editing. **Davide Gottardi:** Methodology, Writing – review & editing. **Oliver Schlüter:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

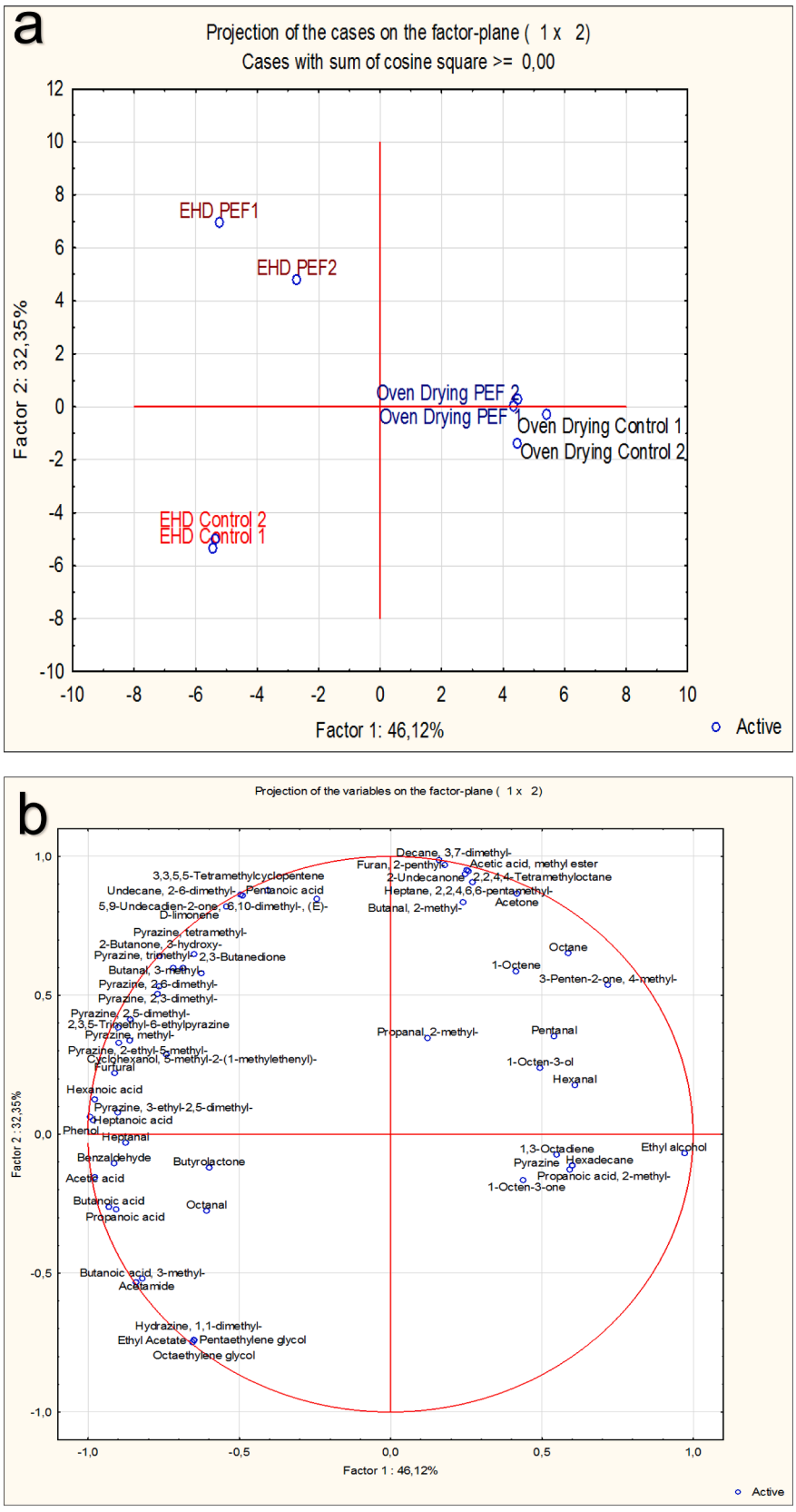

Fig. 2. Projection of cases (a) and variables (b) obtained by PCA elaboration of volatile molecules of the samples that were generated from each processing pathway, samples treated with PEF or untreated (control) and dried with oven drying or EHD drying. The data are shown in duplicate (1, 2).

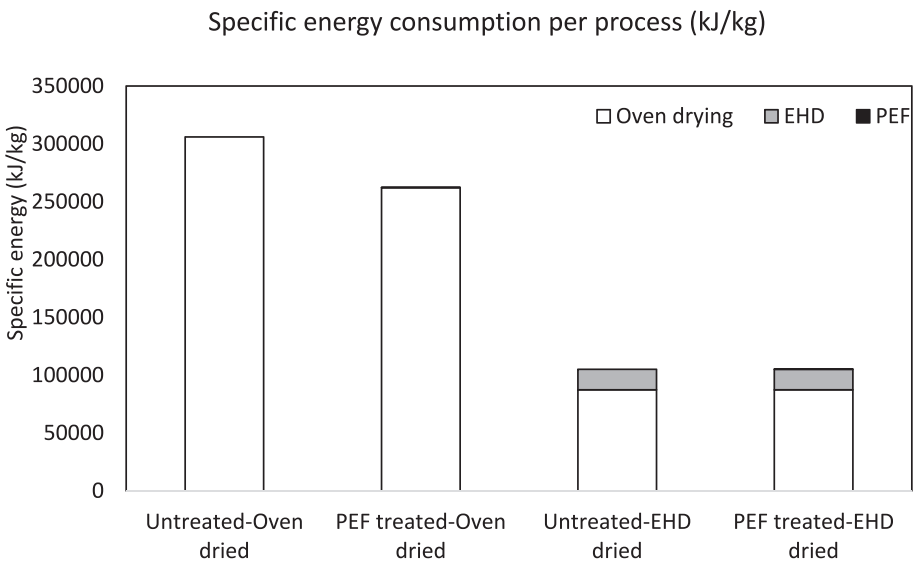

Fig. 3. Energy consumption of the processing pathways that were used for the cricket samples.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2023.138276.

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