Pérez-Won *et al.*
Food Production, Processing and Nutrition (2024) 6:21
https://doi.org/10.1186/s43014-023-00202-8

Food Production, Processing and Nutrition

RESEARCH **Open Access**

Vacuum microwave drying of PEF-pretreated Chilean abalone (*Concholepas Concholepas*) slices: drying features, sustainability parameters, and protein quality properties

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Abstract

A pulsed electric field (PEF: 2.0 kV/cm) was applied before vacuum microwave drying (VMD: 120 W, 120/260 W, and 260 W at 40 kPa) on Chilean abalone mollusks. PEF and VMD effects on process features (drying kinetics, modeling, and sustainability) and product quality (texture, structure, and digestibility) were measured. The PEF application increased moisture diffusivity by up to 27% in the combined PEF+VMD process. According to the statistical analysis applied to all mathematical models, the Logarithmic model was best fitted to VMD experimental values. In terms of energy consumption, applying PEF+VMD reduced energy consumption by up to 33% of the 120W and 120/260W non-PEF samples. The best values for the rehydration index were obtained with the 120/260W (45%) and PEF+120/260W (61%) treatments. In addition, these samples had the best texture parameters. The PEF+120/260W treatment showed the highest degree of hydrolysis (11%) for the calculated protein efficiency. Finally, using PEF as a pretreatment in a VMD process can be cost-effective for scale replication due to its time efficiency and product quality to Chilean abalone samples.

Highlights

- PEF applied previously to the VMD process reduced process time.
- Microwave power during the VMD process decreased energy consumption.
- PEF pretreatment affected the rehydration indexes of dried Chilean abalone.
- VMD process did not affect the protein content of Chilean abalone.

Keywords Chilean abalone, PEF treatment, VMD process, Drying kinetics, Energy consumption, Structural properties, Protein hydrolysis

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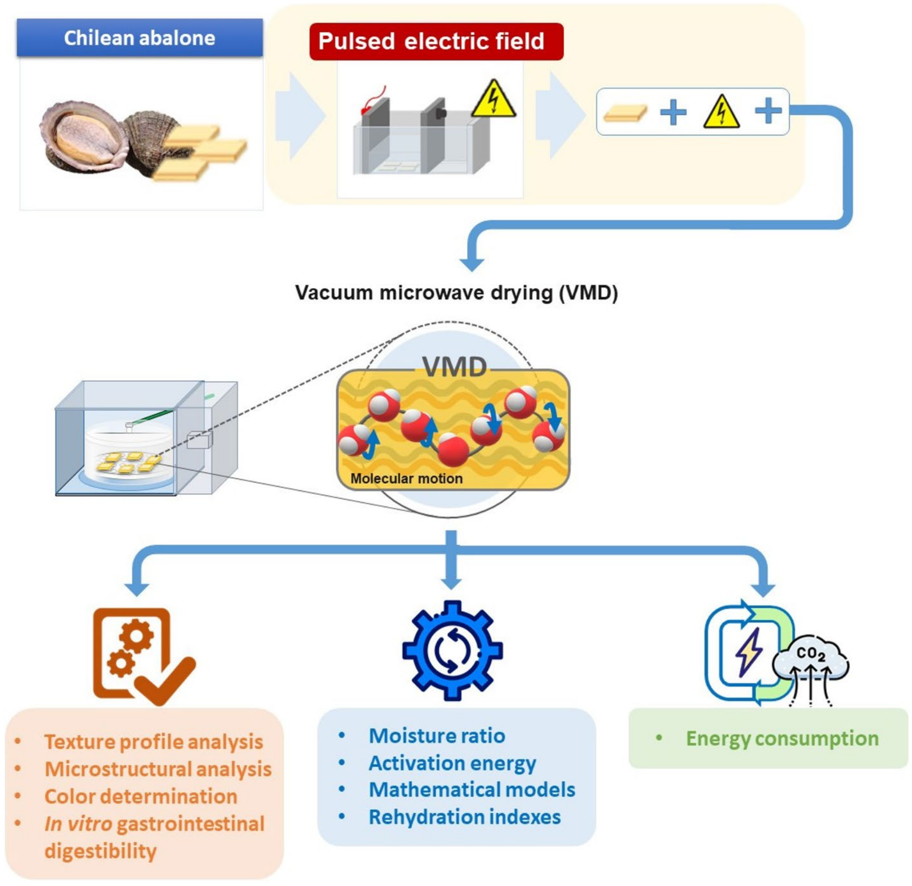
Graphical Abstract



Introduction

The Chilean abalone (*Concholepas concholepas*) belongs to the Muricidae family of Sobeoconcha, an endemic species growing in Chile and Perú coasts. Likewise, this mollusk has a high commercial value in gourmet markets own to its texture and flavor characteristics, which are recognized as significant quality indicators (Palma-Acevedo et al. 2022). However, as is well known, marine products are very susceptible to deterioration and decomposition (Siripatrawan et al. 2009) due to high water content (>85%) and water activity (>0.90).

Drying can avoid the growth of microorganisms by reducing water activity by decreasing water content and avoiding potential deterioration and contamination during extended storage. (Kipcak & İsmail 2020). Several drying methods have been applied to marine products, including traditional methods using sources like sun, hot air, and smoke, and most current methods, such as freeze-drying, vacuum drying, and fluidized bed drying. The hot air drying (HAD) method is doubtless the most accepted drying method in the fishery industry due to being easy to implement, operate and maintain and less expensive for machines, equipment, and systems for processing (Wang et al. 2012). However, HAD has some drawbacks, like higher energy consumption and a long drying period, which results in low-quality products due to surface hardening (Chen et al. 2013; Viji et al. 2019). In addition, there is a need to develop different sustainability approaches to evaluate drying methods. This way, novel combined drying techniques have been built up and started in the fishery industry, e.g., combined vacuum and microwave techniques or infrared-assisted HAD method. The VMD system is an innovative hybrid drying system, with the advantage of heat formation occurring directly within the food matrix, thus reducing drying time by 70-90% compared to HAD and freeze-drying methods (Giri & Prasad 2007; Richter Reis 2014; González-Cavieres et al. 2021).

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The principle of the VMD technology consists of the interaction of the microwaves emitted by the magnetron with the food; the microwaves are absorbed by the polar molecules in the food matrix, such as water molecules. This interaction with polar molecules with a high dielectric property absorbs microwave radiation energy and transforms it into heat through the accelerated movement of these molecules, raising the temperature of the food (González-Cavieres et al. 2021). This reaction triggers a phase change of the water in the food matrix, resulting in thermal dissipation towards the non-polar molecules by convective heat conduction (Li et al. 2019).

On the other hand, during the microwave heating process, the reduction of the pressure exerted by the vacuum pump results in rapid evaporation of the water by decreasing the temperature of this phase change. In this way, the VMD method can be applied at lower temperatures than other drying methods, avoiding loss of product quality (Monteiro et al. 2018).

Wiktor et al. (2013) and Palma-Acevedo et al. (2022) mentioned that applying a pulsed electric field (PEF) previously increased for plant and marine food, respectively, the mass transfer rate for drying processes such as freeze-drying. The principle of PEF consists of applying pulsed (intermittent) electric fields of large amplitude in a food matrix (Blahovec et al. 2017). The electrical fields generate partial or permanent alterations in the quality properties of the food products, especially structural features. Electroporation (formation of temporary or permanent pores) eventually leads to increased cell membrane permeability, which enables the exchange of ions and other molecules (Aykın Dinçer 2021). PEF has been used for food pasteurization, non-thermal microbial inactivation, recovery of high-value biocompounds from plant food, and as a pretreatment to decrease the processing times, e.g., freezing, drying, and frying (Arshad et al. 2020; Arshad et al. 2021).

In this context, combined or assisted technologies are interested in decreasing process times and improving the seafood drying process, such as PEF previously applied to the VMD process. This study aimed to evaluate the influence of a PEF pretreatment under different conditions of the VMD process on the drying characteristics, sustainability parameters, and protein quality of Chilean abalone slices.

Materials and methods

Raw material and PEF pretreatment

Chilean abalone samples were purchased from a local Coquimbo city market (Chile). First, the mollusks were cleaned (without shells) and selected for their length (≤12 cm). Then, they were sliced (20×30×3 mm) and stored at 4.0±0.2°C for 48 h before processing. Moisture content was determined by the AOAC Official Method 934.06 (AOAC. 1990). The PEF pretreatment with a batch process (EPULSUS PM1-10, EnergyPulse Systems, Ltd., Lisbon, Portugal) was performed with a cubic cell (10×10×5 cm) with two stainless-steel electrodes (10×10 cm) placed at the lateral ends of the cell with a 5 cm separation. Then, samples (15.0±0.3 g, approx.) were placed in the cell with 250 mL water and NaCl solution (electrical conductivity = 1 mS/cm) at 20.0±0.2°C. Hence, the PEF operating conditions were 15 µs wide, 50 pulses, 1 Hz frequency, and 2.0 kV/cm electric field (Palma-Acevedo et al. 2022). Following PEF treatment, electropored samples were lifted from the chamber, and then they were placed on the tray of the VMD dryer.

VMD process

The VMD process was carried out with a vacuum microwave dryer (Fig. 1) designed and built in the Food Engineering Department of Universidad del Bío-Bío, which has a control unit for setting the power (700 W) and frequency (2.45 GHz). The VMD system devices are a microwave oven (TH18B05, Thomas, Shanghai, China), vacuum pump (Ffi12 Hbk, Embraco, São Paulo, Brazil), pulse controller (DH48S-S, CKC-TINNER, Shanghai, China), and a pure Teflon (PTFE) vacuum chamber (dielectric constant of 2.1) with a 1500 cm^3. Also, the VMD system used a regulating valve and a vacuum gauge to control the pressure. As for experimental tests, three different power rates were used

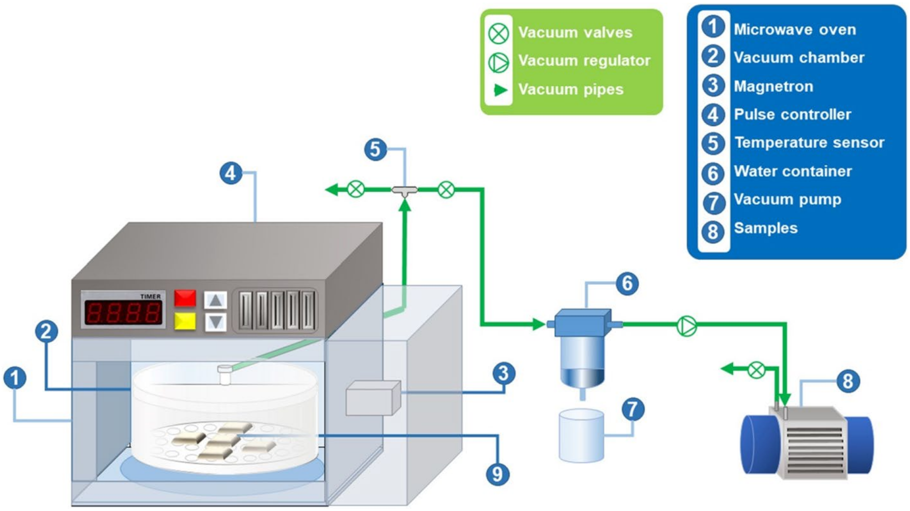

Fig. 1 Schema of the vacuum microwave drying (VMD) system

for the drying conditions: 120 W and 260 W, and a special cycle was performed at a higher power of 120/260W (Lech et al. 2015) under the same vacuum pressure conditions, 40 kPa. The latter situation was a variable power ratio, which used 50% of the initial processing time at 120 W and the remainder of the processing time at 260 W. The sample weight record was performed every 5 min (Taskin et al. 2019; Zaki et al. 2007) using an analytical balance (±0.0001 g) after turning off the VMD system. The moisture content of Chilean abalone samples decreased from 3.20 to 0.01 g/g db (dry basis).

Drying features

Drying kinetics and mathematical modeling

During the VMD process, the moisture ratio (MR= $(X_t - X_e) - (X_o - X_e)$) was determined by Eq.1. The moisture diffusion from the samples can be expressed by Fick's second equation for non-stationary diffusion (Karathanos et al. 1990). A constant unidirectional moisture diffusion, negligible shrinkage, and power change during the VMD process were assumed for the calculation, which resulted in the analytical solutions in Eq. 1 for an infinite plate geometry and extended drying times (Darvishi et al. 2013). Then, VMD kinetics modeling was performed by three equations widely used in most food drying processes (Sarimeseli 2011; Çağlar et al. 2009). The mathematical models applied were Henderson and Pabis (Eq. 2), Logarithmic (Eq. 3), and Two-Term (Eq. 4).

$$MR = \frac{X_t - X_e}{X_0 - X_e} \rightarrow MR = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}e^{\left(-\frac{(2n+1)^2\pi^2 D_{eff}}{4L^2}t\right)} \tag{1}$$

$$MR = a\ e^{(k\ t)} \tag{2}$$

$$MR = a\ e^{(-k\ t)} + c \tag{3}$$

$$MR = a\ e^{(-k_o\ t)} + b\ e^{(-k_1\ t)} \tag{4}$$

MR: moisture ratio (dimensionless), X_t: moisture content at any time (g water/g sample), X_o: initial moisture content (g water/g sample), X_e: equilibrium moisture content (g water/g sample), D_{eff}: moisture effective diffusivity (m^2/s), *L*: thickness of sample sheets (m), *a, b, and c*: models constants of models (dimensionless), *k*, k_o, *and* k_1: kinetic parameters of models (min^{-1}).

The fit quality of the experimental data to the mathematical models proposed for VMD drying kinetics were evaluated using the determination coefficient (R^2) together with reduced Chi-square (χ^2, Eq. 5) and Root Mean Square Error (RMSE, Eq. 6) (Darvishi et al. 2013).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2\right]^{1/2} \tag{5}$$

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N - Z} \tag{6}$$

$MR_{exp,i}$: experimental moisture ratio, $MR_{pre,i}$: predicted moisture ratio, *N*: observed number, *Z*: number of model constants.

Energy consumption

The energy consumption of the VMD process was determined according to Motevali et al. (2011) with some modifications. Thus, E_1 represents the microwave system consumption (Eq. 7), E_2 is the power consumed by the vacuum pump (Eq. 8), E_3 is the PEF process (2.0 kV/cm) generating a energy fixed consumption of 0.054 kWh, and E_t represents the total drying process consumption ($E_t = E_1 + E_{2+} E_3$). Moreover, there are other energetic parameters of high interest for drying processes, such as the specific energy consumption (SEC), defined as the energy required (kW) to eliminate 1 kg of water from the product (Eq. 9) (Torki-Harchegani et al. 2016), the moisture extraction rate (MER) described as the water removed (kg) during drying time (MER = m_w/t), and the specific moisture extraction rate (SMER) explained as the water released (kg) during drying for the total energy supplied per kWh (SMER = m_w/E_t) (Boateng et al. 2021).

$$E_1 = p \times t \tag{7}$$

$$E_2 = L \times t \tag{8}$$

$$SEC = \frac{E_t}{m_w} \tag{9}$$

p: microwave output power (kW), L: nominal pump power (kW), t: drying time (h), m_w: mass of water removed (kg)

Protein quality properties

Rehydration indexes

Samples dried by the VMD process were boiled at 100°C in distilled water during 6 h with 1:50 solid-to-liquid ratio. The rehydration index (R_{reh}) and recovery index (R_{rec}) were used to determine the rehydration capacity as expressed in Eqs. 10 and 11, respectively (Deng & Zhao 2008; Duan et al. 2011; Wei et al. 2020)

$$R_{reh} = \frac{\mathrm{W}_{ar} - \mathrm{W}_{ad}}{\mathrm{W}_{ad}} \times 100 \tag{10}$$

$$R_{rec} = \frac{W_{ar}}{\mathrm{W}_{\mathrm{bd}}} \times 100 \tag{11}$$

W_{ar}: samples' weight after rehydration (g), W_{ad}: samples' weight after the drying process (g), W_{bd}: dried samples' weight before drying (g).

Texture profile analysis (TPA)

A TA-TX PLUS texture analyzer (Texture Tech., Scarsdale, NY, USA) was used for this evaluation, and data were automatically recorded with the Texture Expert v.2.63 software (Stable Micro Systems Ltd.). The hardness, cohesiveness, springiness, and chewiness parameters were determined for all rehydrated Chilean abalone samples (rehydration conditions were 6°C for 4 h in ddH_2O). Samples were compressed twice to 75% of their original thickness at a speed of 1 mm/s with a 35 mm diameter aluminum cylinder under five instrumental replicates (Briones-Labarca et al. 2012).

Microstructural analysis

A SU3500 Scanning Electron Microscopy equipment (Hitachi, Tokyo, Japan) was used for this analysis. Each sample was cut in a thin, uniform cross-section with a scalpel and placed on a watch glass. Then, these pieces were deposited on double-sided carbon fiber tape, which provided higher-quality micrographs. Last, these pieces were put in on the sample holder of the SEM equipment and placed in its vacuum chamber. The equipment works with a calibrated magnification of 65X and a length of 500 µm as optimal conditions for capturing micrographs.

Determination of the degree of hydrolysis

Degree of hydrolysis First, the total protein content was determined by the AOAC G. (2016)using the Kjeldahl method (Eq. 12). The degree of hydrolysis (DH, Eq. 13) was determined according to Nielsen et al. (2001) with some modifications. The DH was measured at intervals of 0, 60, 90, and 120 min. The OPA (σ-phthaldialdehyde 97.0%. Art.P1378 Sigma-Aldrich, St. Louis, MO, USA) reagent was prepared by dissolving 160 mg OPA in 4 mL of ethanol 95.0% (Art. 1.085437769 Sigma-Aldrich, St. Louis, MO, USA) and added to a previously prepared solution consisting of 7.62 g borax (Na_2 $[B_4O_5$ $(OH)_4]$-$10H_2O$) and 200 mg SDS ($NaC1_2$ H_2 $5SO_4$) dissolved in 150 mL deionized water (0.9516 meqv/L). To the previously mixed solutions, 176 mg of 99% dithiothreitol (DTT) was added and bottled in a 200 mL volumetric flask. The final reagent was stored in an amber bottle and used the same day. A calibration curve was derived with a 50 to 200 mg/mL L-serine solution (Art.7769 Merck, Darmstadt, Germany) (Nielsen et al. 2001). The assay was performed by pipetting 0.5 mL of the sample into a 1 mL Eppendorf tube and centrifuging at room temperature during 20 min and 14.0 g. Some 200 µL of supernatant was mixed with 1.5 mL OPA reagent for subsequent absorbance measurements at 340 nm with a spectrometer (Genesys 10S UV-Vis, Thermo Fisher Scientific Inc., Madrid, Spain) after 3 min of incubation at room temperature.

$$\%Prot = \frac{[H_2SO_4] \times (V_f - V_i) \times F}{w_s} \tag{12}$$

$$DH = \frac{h}{\mathrm{h}_{\mathrm{tot}}} \times 100 \tag{13}$$

$$h = \frac{Serine\ NH_2 - \beta}{\alpha} \times 100 \quad (14)$$

Where: $[H_2SO_4]$ is titrated solution concentration, V_f: final volume, V_i: initial volume, F: protein source factor (×6.25), serine NH_2: serine NH_2 m_{eqv} /$g_{protein}$, α, and β published by Nielsen et al. (2001) for specific raw materials.

Digested protein efficiency The calculated protein efficiency ratio (C-PER) was determined with the procedure described by Satterlee et al. (1982), using Eq. 15 (Sindayikengera & Xia 2006; Chávez-Mardones et al. 2013). To determine essential amino acid (EAA) was performed following the methodology described by Bidlingmeyer et al. (1984). It was expressed as a standard FAO/WHO percentage. Subsequently, the $\%EAA_{FAO}$ was adjusted. If all $\%EAA_{FAO}$ is ≤100%, generally continue with the calculation using Eqs. 16 and 17; however, if $\%EAA_{FAO}$ ≥100%, reduce to 100% and continue with the same equations (Phimphilai et al. 2006).

$$\%EAA_{FAO} = \frac{\left[\frac{gEAA}{100\ gprotein}\right] \times [in\ vitro\ protein\ digestibility]}{FAO/WHO\ std.\ for\ that\ EAA} \quad (15)$$

$$X = \sum \left(\frac{1}{[\%EAA_{FAO} \times [associated\ weight]]} \right) \quad (16)$$

$$Y = \sum (associated\ weight) \quad (17)$$

Statistical analysis

The Statgraphics® Plus 5.1 software was used for the analysis of variance (ANOVA) between the means of the drying, energy, and protein quality parameters at a confidence level of 95%, applying Tukey's test (p<0.05). Moreover, the multiple range test (MRT) was used to determine possible homogeneous groups among the parameters.

Results and discussion

Drying curves and diffusivity

Figure 2 shows the moisture content variation of Chilean abalone samples over the drying process. The moisture content of Chilean abalone samples decreased from 3.20±0.12 to 0.01±0.00 kg water/kg db. The samples were subjected to different power conditions, and the increase in power was inversely proportional to processing time. Wan et al. (2013) reported a similar behavior when they evaluated the drying of grass carp fillets and showed that the microwave power intensity significantly affected the

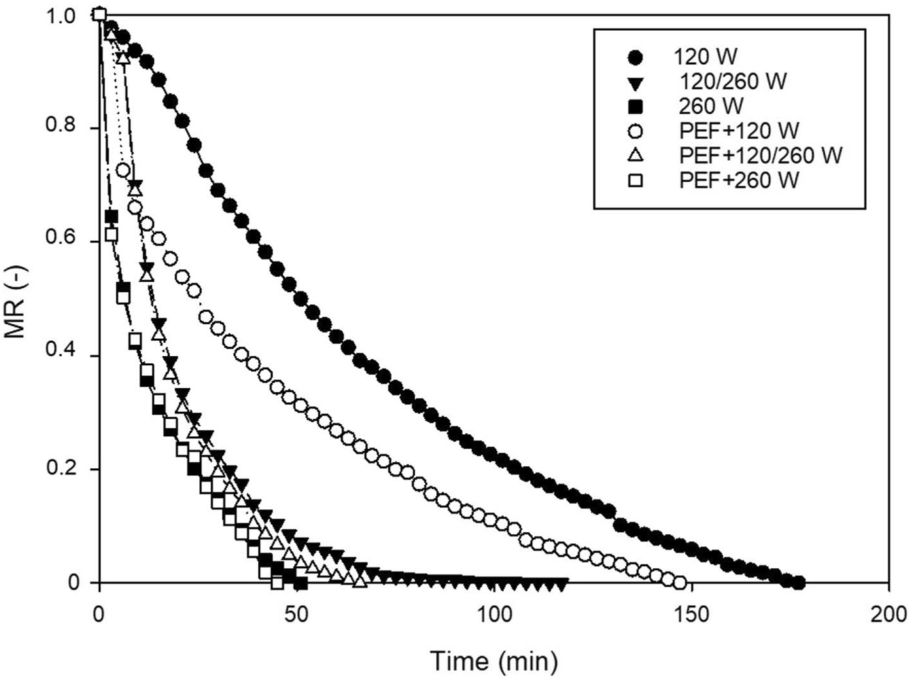

Fig. 2 Drying curves behavior (MR vs. time) of Chilean abalone under different VMD conditions (120, 120/260, and 260 W) with and without PEF pretreatment

drying process behavior. The higher power of the VMD in a food matrix with high moisture content enhances the absorption of microwave energy because of the dipolar molecule arrangement that facilitates its diffusion to the medium (Wan et al. 2013). Moisture diffusivity values for samples without the PEF pretreatment were 2.19, 2.91, and 4.38×10^{-9} m^2/s for the 120 W, 120/260 W, and 260 W treatments, respectively. Samples pretreated with PEF increased moisture diffusivity by 7.4 to 27.26% compared to samples without PEF pretreatment. PEF pretreatment increased moisture diffusivity at 120 and 120/260 W treatment; however, for 260 W, the values showed no difference ($p>0.05$) (Fig. 2). Regarding quality, reducing drying time in meat products is an advantage. It has been reported that microwave drying could prevent lipid oxidation, reduce the deterioration of meat product quality, and thus maintain their nutritional value (Contini et al. 2014).

Drying kinetics modeling

The drying curves (MR vs. time) under different VMD conditions are shown in Fig. 2, which were fitted over time to the Henderson and Pabis, Logarithmic, and Two-Term models. Table 1 shows the evaluation of the results of the nonlinear regression analysis, which is based on the values of χ^2, RMSE, and R^2. The mathematical model showed a well-acceptable with high R^2 and low χ^2 and RMSE values (Ahmat et al. 2015; Osae et al. 2019). The Logarithmic and Two-Term models were better fitted to the drying curves. The Logarithmic model showed the highest fit with an R^2 equal to 0.9986 for treatments with low power (120W). In contrast, the highest R^2 value was achieved by the Two-term model for treatments with high power (260W) (Table 1). When comparing the mean values of these criteria, R^2, χ^2, and RMSE, between VMD and PEF+VMD treatments, the Logarithmic model had better R^2 values, the lowest $\chi^{2,}$ and RMSE for the samples dried by VMD - the VMD process without the PEF pretreatment. Ahmat et al. (2015) and Kipcak and İsmail (2020) considered that the Logarithmic model represents better the microwave drying behavior of food products, specifically marine products. For the samples pretreated with PEF (PEF+VMD), the Two-Term model could better represent the drying behavior by PEF+VMD processes (Table 1).

Sustainability parameters

Saving energy in drying processes has become increasingly widespread in recent years (Sunjka et al. 2004; González-Cavieres et al. 2021). Both energy savings and the emissions factor should be parameters that should be considered in the fishery industry. Table 2 shows the SEC, SMER, and MER values in the drying process. Energy consumption (kWh) for the drying processes (VMD and PEF+VMD) ranged from 0.09 to 0.28 kWh (Table 2). The treatments showed significant differences ($p<0.05$), except between the treatment 260

Table 1 Mathematical model parameters and statistical tests for MVD and PEF+MVD processes

Model	Treatment	a	b	c	d	R^2	RMSE	X^2
Henderson and Pabis	120 W	1.0966	0.0162	-	-	0.9876	0.0335	0.0011
	120/260 W	1.0906	0.0530	-	-	0.9897	0.0280	0.0008
	260 W	0.8909	0.0704	-	-	0.9701	0.0429	0.0018
	PEF+120 W	0.8999	0.0219	-	-	0.9801	0.0346	0.0012
	PEF+120/260 W	1.1094	0.0586	-	-	0.9828	0.0408	0.0017
	PEF+260 W	0.8780	0.0692	-	-	0.9578	0.0507	0.0026
Logarithmic	120 W	1.1979	0.0116	-0.1524	-	0.9986	0.0114	0.0001
	120/260 W	1.0924	0.0521	-0.0054	-	0.9899	0.0278	0.0008
	260 W	0.8788	0.0792	0.0301	-	0.9720	0.0426	0.0018
	PEF+120 W	0.9059	0.0209	-0.0132	-	0.9803	0.0340	0.0012
	PEF+120/260 W	1.1331	0.0524	-0.0421	-	0.9854	0.0373	0.0014
	PEF+260 W	0.8616	0.0783	0.0337	-	0.9594	0.0525	0.0028
Two-term	120 W	0.5802	0.0162	0.5164	0.0162	0.9876	0.0335	0.0011
	120/260 W	0.5669	0.0530	0.5237	0.0530	0.9897	0.0280	0.0008
	260 W	0.2676	0.7537	0.7325	0.0577	0.9948	0.0201	0.0004
	PEF+120 W	0.2101	0.2396	0.8171	0.0199	0.9896	0.0262	0.0007
	PEF+120/260 W	0.5816	0.0586	0.5277	0.0586	0.9828	0.0408	0.0017
	PEF+260 W	0.2702	0.5332	0.7298	0.0569	0.9915	0.0290	0.0008

R^2 Coefficient of determination, *RMSE* Root mean square error, X^2 Chi-square

Table 2 Energy and sustainability parameters of VMD and PEF+VMD treatments

Treatment	Time process (min)	Consumption (kWh)	SEC (kWh/kg)	SMER (kg/kWh)	MER (kg/h)
120 W	183	0.28 ± 0.00^{a}	35.67 ± 0.71^{a}	0.028 ± 0.01^{d}	0.003 ± 0.00^{c}
120/260 W	107	0.18 ± 0.00^{c}	15.12 ± 0.43^{c}	0.066 ± 0.002^{c}	0.007 ± 0.00^{b}
260 W	54	0.09 ± 0.00^{e}	7.02 ± 0.61^{e}	0.143 ± 0.001^{a}	0.014 ± 0.001^{a}
PEF+120 W	147	0.26 ± 0.00^{b}	25.72 ± 2.49^{b}	0.0039 ± 0.004^{d}	0.004 ± 0.00^{bc}
PEF+120/260 W	66	0.12 ± 0.01^{d}	9.19 ± 0.95^{d}	0.110 ± 0.012^{b}	0.012 ± 0.001^{a}
PEF+260 W	51	0.09 ± 0.00^{e}	7.15 ± 3.35^{de}	0.014 ± 0.002^{a}	0.014 ± 0.001^{a}

SEC Specific energy consumption, *SMER* Specific moisture extraction rate, *MER* Moisture extraction rate. Different letters in the same column indicate that the values are significantly different (p<0.05)

W and PEF+260 W (p>0.05), which presented the lowest energy consumption (0.09 kWh). Kipcak & İsmail (2020) stated a similar energy consumption behavior when drying fish, chicken, and beef; they considered energy consumption proportional to the power used. Başlar et al. (2014) using ultrasonic vacuum drying processes could generate advantages in energy efficiency and beef and chicken quality. PEF application as a pretreatment for VMD in Chilean abalone, the energy consumption at 120 W and the 120/260 W was reduced by 7.14 and 33.33%, respectively.

The SEC values ranged from 7.15 to 35.67 (kWh/kg), which determined that the 120 W treatment had the highest consumption per kg of water removed. Similar behavior was obtained with the treatments applying PEF, but with a reduction of up to 27.89% compared with the treatments without PEF (Table 2). For SMER and MER values, samples treated with a power higher than 120 W presented better values, thus decreasing the specific extraction consumption and increasing the MER due to the reduction of the drying period (Alibas 2007; Kipcak & İsmail 2020). In addition, there were no significant differences with the samples pretreated with PEF (p>0.05) (Table 2). Results concur with those reported by Sharma & Prasad (2006) for garlic cloves and Motevali et al. (2011) for pomegranate arils.

Rehydration indexes

Rehydration capacity is an important quality parameter of dried food that can determine the damage caused by some drying process (Al-Khuseibi et al. 2005; Taskin et al. 2019). Figure 3 shows the results of the recovery ratio and rehydration ratio of the different VMD and PEF+VMD treatments. The best values for the recovery ratio were 45.09% (120/260W) and 61.48% (PEF+120/260W). The other drying conditions with 120 and 260 W showed no significant differences (p>0.05) (Fig. 3). PEF application can improve the recovery rate by 34.36% for combined powers; however, extreme ranges of powers such as 120 and 260 W decreased between

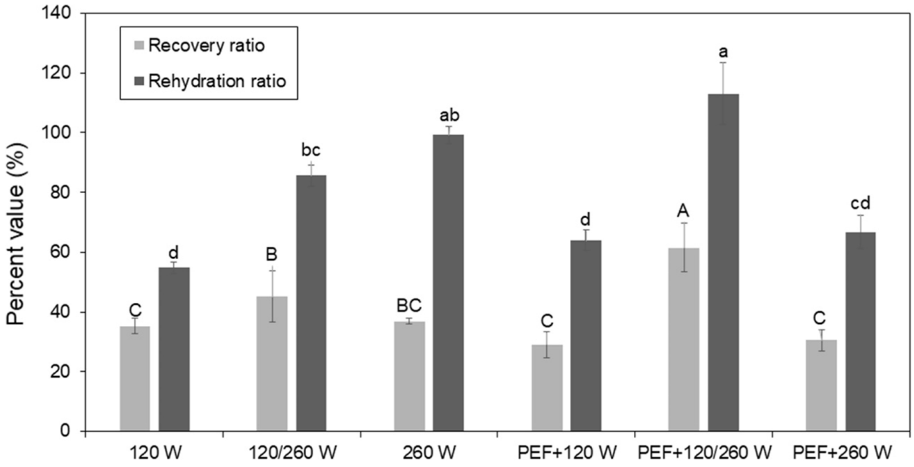

Fig. 3 Recovery and rehydration rate of dried Chilean abalone samples treated by VMD and PEF+ VMD under different powers (120 W, 120/260 W, and 260 W). Different uppercase letters and lowercase letters, indicate significant differences when p < 0.05 for the recovery rate of samples with and without PEF application

17.62 and 17.33%, respectively. The increased recovery rate value improved product quality (Deng & Zhao 2008; Doymaz 2011). Wang et al. (2018) determined that using pretreatments in VMD reduced the formation of porous structures in the food matrix, which is a critical factor for water-holding capacity (Wang et al. 2018; Ye et al. 2017). The PEF+120 W and PEF+120/260 W powers increased between 14.39 and 24.28% when comparing the rehydration rate value of the VMD and PEF+VMD treatments (Fig. 3). Rehydration decreased by 32.77% for high powers such as 260 W. Zhu et al. (2021) described that the factor that is attributable to a low rehydration index is the application of aggressive powers >1000W (Tian et al. 2015). These generate damage in the structure because microwave radiation is absorbed in the food matrix to produce rapid internal vaporization and internal tissue damage (Deng & Zhao 2008; Zhu et al. 2021).

Texture analysis

One of the main characteristics of Chilean abalone is the hardness of the meat, an attribute that must be modified for it to be consumed. Hardness, springiness, and chewiness are essential for rehydrated meat and seafood products; when these values are closer to the fresh product's values, the dried product's quality is better (Wang et al. 2012). Table 3 shows the different TPA values for rehydrated Chilean abalone samples. The 260 W treatment obtained the lowest hardness value, 51.14% less than the fresh sample (Table 3). It showed significant differences with the other treatments ($p<0.05$), except for the PEF+120 W treatment, which showed no differences ($p>0.05$). Gómez et al. (2019) studied PEF applied to meats in which the tenderization process was improved with increased proteolysis. Using low power in the drying process prevented rapid water loss that could increase hardness and springiness (Duan et al. 2011; Li et al. 2019). For the springiness and cohesiveness, the VMD and PEF+VMD processes didn't show significant differences from each other ($p>0.05$), but they showed differences compared with the raw sample ($p<0.05$). Palma-Acevedo et al. (2022) determined TPA for cooked Chilean abalone, with Chewiness values of 18.90±1.41 cm and hardness of 216.0±15.4 N; similar values were obtained with the PEF+120 W treatment (Table 3). Song et al. (2017) and Yu et al. (2022) reported similar values of cohesiveness and elasticity in abalone var. *Haliotis discus* Hannai. There was similar behavior between hardness and chewiness values when evaluating data from VMD and PEF+VMD processes (Table 3). From Table 3, the 260 W treatment had the lowest hardness and chewiness values; thus, this treatment did not generate significant changes.

Microstructure analysis

The microstructural changes of Chilean abalone samples can also be used to assess the damage caused by the VMD and PEF+VMD processes. Figure 4 illustrates the scanning electron microscopy of the Chilean abalone samples treated by VMD and PEF+VMD. Image analysis indicated that the structure was affected under different VMD powers. The application of low power, such as 120 W, caused less damage when compared with the highest power at 260 W. Pankyamma et al. (2019) informed that working with low microwave power on yak meat, the muscle structure damage could be controlled for higher benefits.

Applying power greater than 200 W exhibited a more significant separation between tissues. The muscle fiber loosens as power increases (Pankyamma et al. 2021). Li et al. (2019) concluded that high power levels, such as high vacuum pressure, caused rapid water evaporation, which resulted in muscle loosening and could lead to muscle rupture. This analysis is accurate for the samples treated with 260 W because the TPA analysis showed that the samples exhibited the lowest hardness value. The 120/260 W treatment showed less damage to its structure. Unlike the other treatments, there was solute migration from the cell tissue to the outside (Fig. 4). This phenomenon is explained by the combined powers (120/260W) that could enhance the migration of the adhered solute from the cell tissue. The presence of this

Table 3 Texture parameters of Chilean abalone samples dried by VMD and PEF+VMD

Treatment	Hardness (N)	Springiness (cm)	Cohesiveness	Chewiness (cm)
Control (Raw)	345.5 ± 45.8^{a}	0.64 ± 0.21^{b}	0.48 ± 0.03^{b}	10.71 ± 2.41^{c}
120W	302.27 ± 56.4^{a}	0.92 ± 0.04^{a}	0.78 ± 0.03^{a}	22.52 ± 5.27^{ab}
120/260 W	396.5 ± 70.3^{a}	0.89 ± 0.03^{a}	0.79 ± 0.02^{a}	21.43 ± 5.09^{ab}
260W	168.8 ± 20.0^{b}	0.95 ± 0.21^{a}	0.81 ± 0.02^{a}	13.15 ± 1.57^{bc}
PEF+120 W	246.4 ± 35.3^{ab}	0.90 ± 0.07^{a}	0.83 ± 0.02^{a}	19.08 ± 3.85^{abc}
PEF+120/260 W	320.74 ± 13.58^{a}	0.94 ± 0.02^{a}	0.79 ± 0.02^{a}	24.38 ± 2.0^{a}
PEF+260W	316.3 ± 20.0^{a}	0.92 ± 0.02^{a}	0.80 ± 0.02^{a}	23.68 ± 1.27^{a}

Different letters in the same column indicate that the values are significantly different ($p<0.05$)

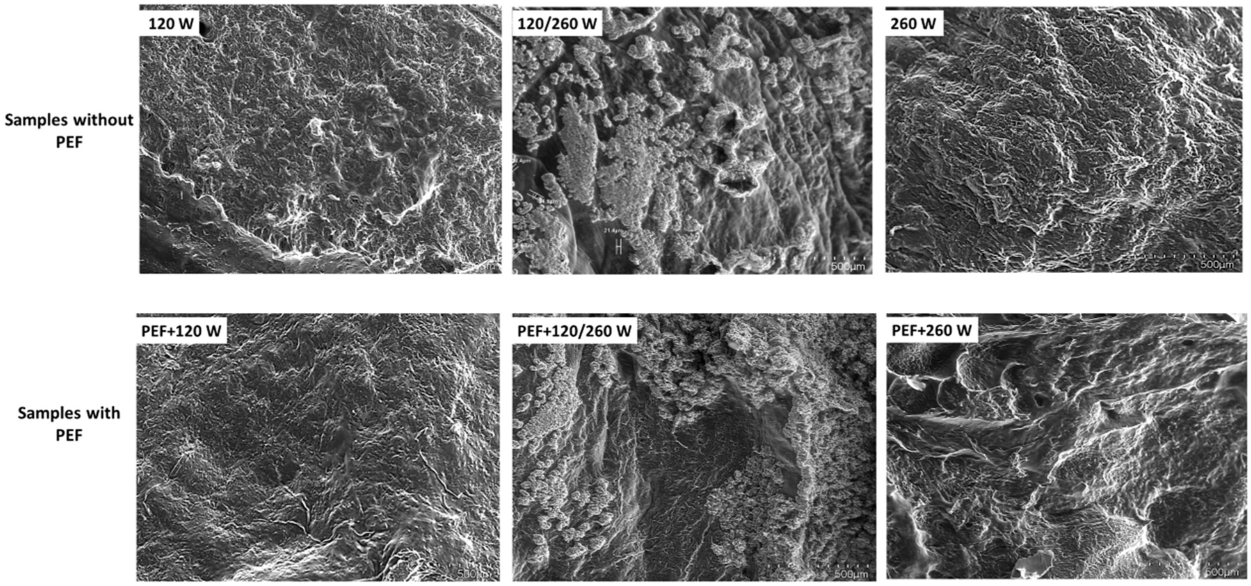

Fig. 4 SEM images (65× 500μm) of Chilean abalone dried by VMD and PEF+VMD process at different powers (120, 120/260, and 260 W)

solute in the medium could be one of the factors that promoted the rehydration process for the 120/260W and PEF+120/260 W treatments (Fig. 3).

Finally, applying PEF in the samples as a pretreatment for the VMD process affected muscle tissue, thus resulting in a more porous, spongy, and irregular structure. These characteristics are directly attributable to the microwave power used in drying (Pawlak et al. 2018; Palma-Acevedo et al. 2022).

In-vitro digestibility

Figure 5 shows the DH of Chilean abalone samples treated by VMD and PEF+VMD. These treatments were selected because of their shorter process times and are shown as drying kinetic curves (Fig. 2). The first stage

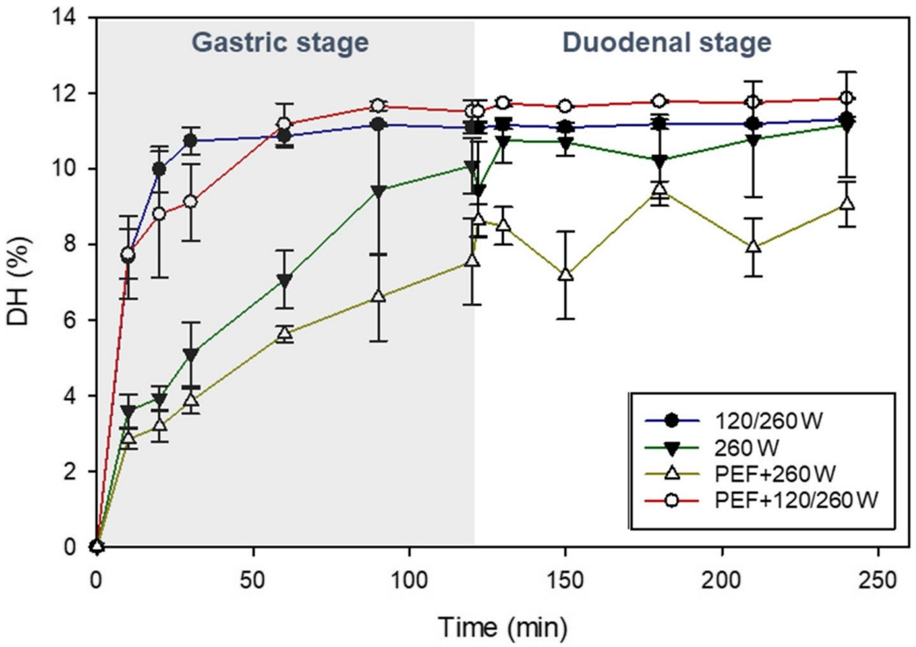

Fig. 5 Degree of hydrolysis (DH) kinetics of Chilean abalone dried samples

was the gastric phase that lasted up to minute 120, and the duodenal phase began at minute 122. Overall, there was a significant difference between the 120/260W treatment and the 260W treatment, whether PEF was applied ($p<0.05$); the highest DH was 11.8±0.02 for the PEF+120/260 W samples. However, if the last 30 min of the drying process is compared, PEF was irrelevant in producing a better DH, but the power combination (120/260 W) made a difference. Palma-Acevedo et al. (2022) showed that applying PEF as a pretreatment to freeze-drying increased DH by approximately 45% and provided a higher C-PER. In other studies related to enzymatic hydrolysis, it has been reported that some reaction products can inhibit catalytic mechanisms by saturating some active sites (Martínez-Montaño et al. 2021), thus leading to a lower DH. It has also been mentioned that more compacted proteins have slower hydrolysis (Guérard et al. 2001). In addition, Oduro et al. (2011) indicated a lower cooking loss when using the microwave treatment, which was higher than grilling or frying; this could coincide with the insolubility of the substrates responsible for protein hydrolysis (Guérard et al. 2001).

Given that DH is directly related to C-PER values, Table 4 shows the percentage protein, C-PER and $\%EAA_{FAO}$ values for the dried Chilean abalone samples. The samples treated by VMD and PEF+VMD presented values ≤ 100% for $\%EAA_{FAO}$. The highest power treatment (PEF+260W) showed the lowest value of $\%EAA_{FAO}$, with significant differences from the treatments (Table 4). The application of higher power in the treatments can cause a higher intensity of thermal processing and temperature, causing a significant decrease in *EAA*, as explained by Luan et al. (2023), who used microwaves to sterilize rainbow trout fillets.

The C-PER was calculated with the final value of DH kinetics (240 min). The protein percent values showed no significant differences between the VMD and PEF+VMD processes ($p>0.05$) with values greater than 40%. The C-PER values varied between 1.15 and 1.21 (Table 4). Alajaji & El-Adawy (2006) indicated similar behavior with C-PER using a microwave treatment compared with freeze-drying when drying vegetable matrices. The C-PER values were attributed to changes in protein bioavailability in each drying process and associated protein denaturation that each technology can perform under its process conditions. Although VMD does not improve DH and the C-PER (Fig. 5), the low partial pressure of oxygen inside the vacuum dryer reduces oxidative deterioration; this enhances the conservation and quality of other nutrients such as polyphenols, lipids, and vitamins (González-Cavieres et al. 2021; Jiang et al. 2017).

Table 4 Protein efficiency ratio (C-PER) for in-vitro digested samples in the duodenal phase

Treatment	Protein (%)	C-PER	EAA_{FAO} (%)
120/260 W	40.20 ± 5.17^{a}	1.15 ± 0.006^{a}	11.13 ± 0.05^{a}
260 W	43.79 ± 9.68^{a}	1.21 ± 0.038^{a}	10.71 ±1.00^{a}
PEF+120/260 W	41.00 ± 5.89^{a}	1.21 ± 0.002^{a}	11.85 ±0.02^{a}
PEF+260W	49.81 ± 1.68^{a}	1.16 ± 0.05^{a}	9.05 ±0.58^{b}

Different letters in the same column indicate that the values are significantly different ($p<0.05$)

Conclusions

This research work assessed and compared the influence of a PEF pretreatment on Chilean abalone under different VMD conditions. Results showed that applying a PEF pretreatment can enhance the mass transfer rate, i.e., less drying time. The 260W power in VMD increased the drying rate and decreased product hardness by 51.14% compared with the raw sample. For energy consumption, 260W and PEF+260W showed the lowest energy consumption values with 0.09 kWh, whereas applying PEF+ VMD reduced energy consumption and CO_2 emissions by up to 33.33% for 120W and 120/260W. For the rehydration rate, using combined powers such as 120/260 W and PEF+120/260 W improved the rehydration process with values higher than 45%. In the case of protein content and calculated protein efficiency (C-PER), the VMD and PEF+VMD processes didn't show differences between the two treatments ($p>0.05$), and protein content percentages were higher than 40%. Finally, the Chilean abalone under vacuum microwave drying (120/260 W) process pretreated with a PEF (2.0 kV/cm) pretreatment was time-saving, energy-efficient, and maintained product quality parameters. Considering all this, this research on the VMD process applied to Chilean abalone could be replicable for other marine products, from fishes to mollusks and crustaceans, including seaweeds, becoming an excellent technology for the drying processes innovation and design and development of the VMD equipment.

Acknowledgments

The authors thank support provided by the Formation of Advanced Human Capital Program through the National Doctoral Degree Scholarship 2020 Folio N° 21201705 (ANID-Chile).

Authors' contributions

Luis González-Cavieres, Erick Jara-Quijada, and Anais Palma-Acevedo conducted the experiments, analyzed data, and wrote part of the manuscript draft. Gipsy Tabilo-Munizaga and Mario Pérez-Won analyzed the results and revised the manuscript. Roberto Lemus-Mondaca designed the study, analyzed data, and revised the manuscript. All authors contributed to the article and approved the submitted version.

Funding
The authors acknowledge the financial support by the Fondecyt Regular N°1201075 project (ANID-Chile).

Availability of data and materials
Data supporting the findings of this study are available upon request from the corresponding author.

Declarations

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Received: 13 July 2023 Accepted: 5 November 2023

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