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Original Article

A new design of square paralelipedic treatment chamber for food processing using pulsed electric field

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ABSTRACT

Today, the influence of pulsed electric field is one of the key components in the PEF treatment process. The manuscript focused on the design and development of new multiple square paralelipedic PEF treatment chamber (TC_2) which houses several electrodes, and testing the efficacy of this chamber on beet juice extraction compared with a single square paralelipedic treatment chamber (TC_1) which houses only two electrodes. The aim of this paper to mention the effect of the Electric Field distribution based on Response Surface Modeling (RSM) for identifying the set point of the juice extraction process using pulsed electric field pre-treatment using a laboratory experimental bench. Obtained results show that the TC_2 of PEF treatment has significant effect not only in juice yield, but also for enhancement of the betanin concentration and saving in consumed energy.

1. Introduction

The pulsed electric field (PEF) technology can be considered as a potential alternative to traditional thermal treatment for food with the advantages of minimising sensory and nutritional damage [1], thus providing fresh-like products [2-4]. The technology involves the application of short pulses (microseconds pulse duration) of high voltage to food sample placed between two electrodes. The applied pulse energy destroys the cell membrane, resulting in the creation of pores called the phenomenon of electroporation with minimal heating of the food [5]. PEF processing has been successfully used for variety of liquids and pumpable food products such as orange and cranberry juices, [6] and apple juice and cider [7] without any loss of their natural characteristics. It has also been successfully used in enhancing juice extraction from apple, sugar beet, and alfalfa [8-10].

The application of electric fields to biological cells in a conducting medium causes buildup of electrical charges at the cell membrane, and consequently a change in the voltage across the membrane. For low electric fields, this causes voltage-dependent gating, the voltage-induced opening of channels in the cell membrane. A flux of ions through the channels, e.g., sodium and potassium ions changes the ion concentrations close to the cell membrane and causes cell stress. The stress for short-duration, low-electric-field electrical signals lasts on the order of milliseconds, and does not cause irreparable damage.

At higher electric fields, and a correspondingly higher voltage across the cell membrane, the permeability of the membrane increases to such a level that either the cell needs from seconds to hours to recover (reversible breakdown), or cell death may occur (irreversible breakdown). The mechanism of this membrane breakdown is not well understood. The most common hypothesis is

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that pores are generated, openings in the membrane of sizes which allow the exchange of macromolecules. Applications of electroporation, the reversible opening of pores which allows for example DNA to enter the cell, are in medicine and biotechnology [11]. The pores may close again after times which could last hours [12] or the damage may, at very high fields, become irreparable, and cell death occurs mainly used in bacteriological inactivation treatment [13].

The pulsed electric field method, applied to the food field, consists in subjecting the food to electric fields of very high intensity (5 to 55 kV / cm), repeatedly (pulsed), for very short periods of time (from order of the microsecond), in order to treat the food products they contain. The food product is placed in the treatment chamber, where two electrodes are connected together with a nonconductive material to avoid electrical flow from one to the other.

Nowadays, despite the fact that the treatment chambers currently used give good performances, a good electric field distribution in the treatment chamber remains a major challenge for the PEF technology to better treat the food.

The main objective of this work is to show that it is possible to give more juice by a new design of treatment chamber with a good quality of betanin and to validate an experimental procedure for optimizing the extraction process using a laboratory experimental set-up, which was successfully used in other research fields for modelling and optimization [14-17].

1.1 Pulsed Electric Field for Electroporation

Exposing a biological cell (plant, animal and microbial) to a high intensity voltage kV using very short pulses (µs to ms) induce the formation of temporary or permanent pores on the cell membrane (figure 1).

This phenomenon, called electroporation, causes the permeabilization of cell membrane i.e. an increase of its permeability and if the intensity of the treatment is sufficiently high, cell membrane disintegration occurs. The mechanism of electroporation is not yet fully understood. Several models have been suggested to explain this complex phenomenon.

The electroporation for permeabilization of the cell membrane is used in many fields such as biotechnology, cell biology, medicine and food industry. Mass transfer processes such as solid-liquid extraction and drying as well as food preservation are important unit operations of the food industry requiring the electroporation of the cell membrane.

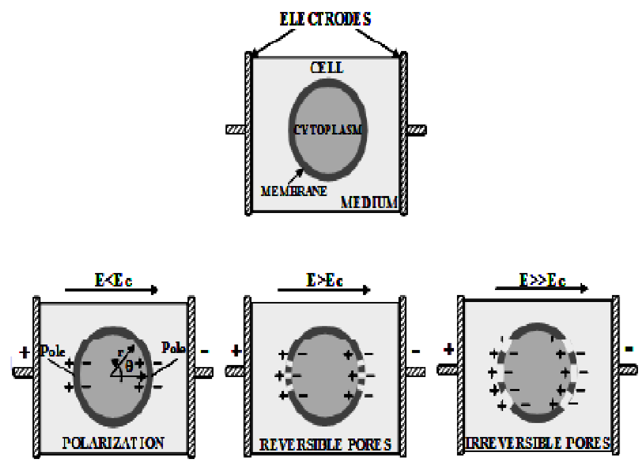


Fig 1. Schematic diagram of a cell exposed to electric field (electroporation process)

2. Materials and Methods

Fresh beets were obtained at local market of fruits and vegetables. After sorting and cleaning operations, they were comminuted with a domestic food processor (Thomson, THMX05736 Model) for 5 min to obtain a homogenous mash. The obtained mash was then kept in a closed vessel to prevent evaporation prior to use. Before each experiment, the mash was properly mixed to obtain a homogenous mixture. It was found that the initial moisture content in the mash was of 62% wet basis.

Figure 2 represents a schematic diagram of the treatment chamber for extraction, which is consisted of an insulated cylinder made of plastic (Teflon, PTFE), 140 mm in length and 70 mm in diameter. The electrodes are constituted by a cylindrical plunger and a disc base of 70 mm diameter having a rigid structure for the juice pressing operation, both made with stainless steel. Extracted juice was filtered through a stainless steel sieve placed on top of the perforated plunger. Juice extracted during pressing was collected in a plastic collector placed under the treatment chamber. The volume of the treatment chamber was 192.3 ml (figure 3).

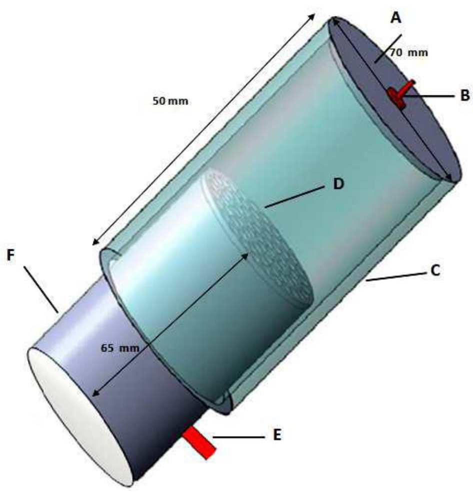


Fig 2. Schematic description of the treatment chamber (All dimensions are in mm). (A) Stainless Steel disk(upper electrode), (B) High voltage connection, (C) Teflon cylinder, (D) Stainless steel sieve, (E) Ground connection, (F) Perforated stainless steel plunger (lower electrode).

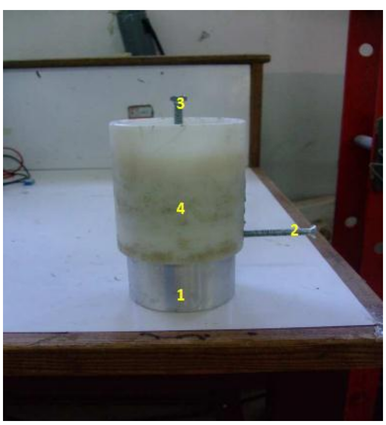


Fig 3. Treatment chamber for extraction used in the experiments: 1- Perforated stainless steel plunger (lower electrode), 2 Ground connection , 3- High voltage connection , 4- Teflon cylinder

For all experiments, the same treatment chamber was used for both pressing and extraction and other treatment chamber for pulsed electric field treatment tests.

The pressure was applied using a hydraulic pressing machine (Mega, 15 tons). Just after PEF treatment, the filled treatment chamber was pressed until a defined pressure of 100 kg/cm2, and was then held at this pressure for 5 min. For all experiments, the thickness of the sample was equal to 2 cm, corresponding to a sample mass of 60 g.

An electronic balance of 0.1 g precision was used to weight the beet juice collected in flacon tubes. During a PEF treatment, the food material is placed between two electrodes forming a treatment chamber and high voltage repetitive pulses are applied across the system in order to achieve membrane breakdown.

2.1. High Pulsed Voltage Treatment

The experimental setup for PEF treatment used in the present work is composed of a couple of components, comprising a high DC voltage source, an energy storage capacitor, a spark gap switch and a treatment chamber. A DC high voltage supply (Spellman 40 kV, 9 mA, Spellman High Voltage Electronics Corporation) charges the bank of capacitors until producing the spark gap's breakdown, causing an abrupt voltage (shock) applied to the load (treatment chamber where the sample is disposed). The storage element composed of three sets of five series capacitors (2 µF, 2 kV), with the possibility to reach a maximum voltage of 10 kV and a total capacitance of 1.2 µF.

For all experiments, the same treatment chamber was used for both pressing and extraction and other treatment chamber for pulsed electric field treatment tests. Pulsed electrical field treatment of the beet mash was achieved by using a PEF generator, represented in Figure 4.

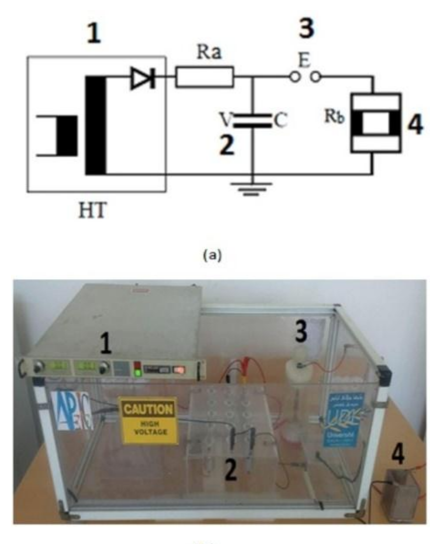


Fig 4. The pulse generator. a) Descriptive schematic of the setup; b) The photography of the setup
1- HV DC power supply, 2-Set of capacitors, 3- Sp ark gap switch, 4-Treatment chamber

A high direct voltage power supply was used to supply and store energy in high voltage capacitors. This energy was subsequently delivered to the treatment with voltage applied recommended using the 15-mm diameter stainless steel spheres of the spark-gap discharger.

Indeed, the high voltage pulsed power supply wave shape used in this study is bi-exponential (figure.5). Also, The propagation velocity of the discharge was determined high volatge value of fall time wich estimed at 500 m/s.

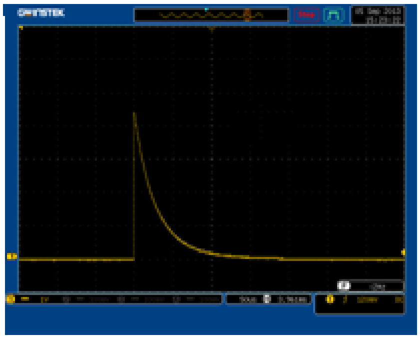


Fig 5.Pulse waveforms delivered by the pulse generator

2.2. Treatment chamber for pulsed electric field treatment tests

Two treatment chambers of different configurations were used in this study, all of which are made of same dimensions of length and width of 60 cm with a height of 100 cm and the same gap between the electrodes.

The square paralelipedic treatment chamber model were developed and compared (TC_2) with the classic treatment chamber (TC_1).

The first configuration TC1 consists of two comprising two parallel metal electrodes (Figure.6). The second model TC_2 comprise four parallel units, consisting of five alternate “ground-HV electrodes" respectively (Figure.7). The model TC_2 is constituted of three units comprising five electrodes: One central HV electrode and two outside ground electrodes. In order to increase the processing capacity and provide an intense electric field for a more effective treatment. .

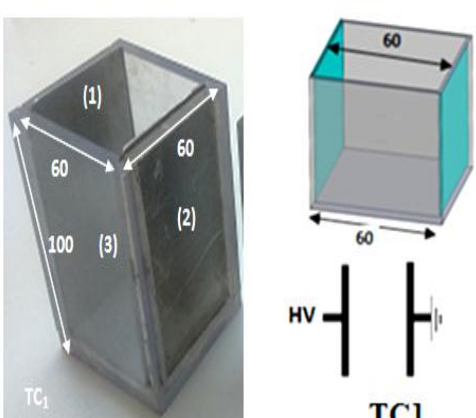


Fig 6. The treatment chamber TC_1 model (Dimensions in mm), 1: HV Electrode. 2: Ground electrode. 3: Plexiglas wall.

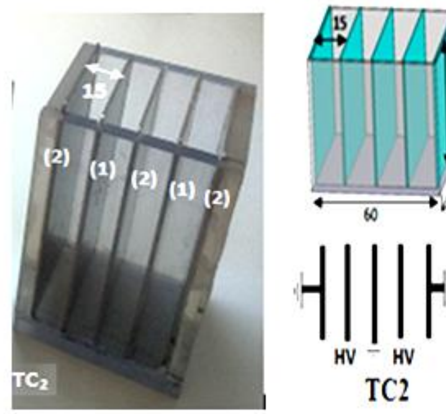


Fig 7. The treatment chambers TC_2 model (Dimensions in mm). 1: HV Electrode. 2: Ground electrode. 3: Plexiglas wall.

3. Results and Discussion

For all the experiments carried out in this section, for each configuration model, one factor was varied while the two other factors were kept at constant values. Thus, figures 8-9 represent the variation of the PEF treatment efficiency, in terms of extracted juice mass (m) and absorbance (Abs) of extracted juice measured at a wavelength λ=530 nm, according to the pulses number n and the capacitor value C respectively for TC_1 model from the same intensity of applied voltage, which was kept constant for all the study of 6 kV for both treatment chambers.

In the same way, in Figures 10 and 11, is represented the evolution of the extracted juice mass (m) and absorbance (Abs) of extracted juice measured at a wavelength λ=530 nm as function of n and C respectively for TC_2 model.

Noted that the absorbance of extracted juice was measured by using of spectrophotometer.

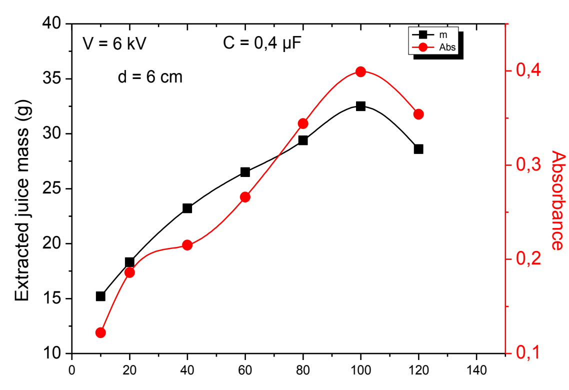


Fig 8. Evolution of the extracted juice mass (m) and Absorbance (Abs) according to the pulses number n for the different TC_1 model

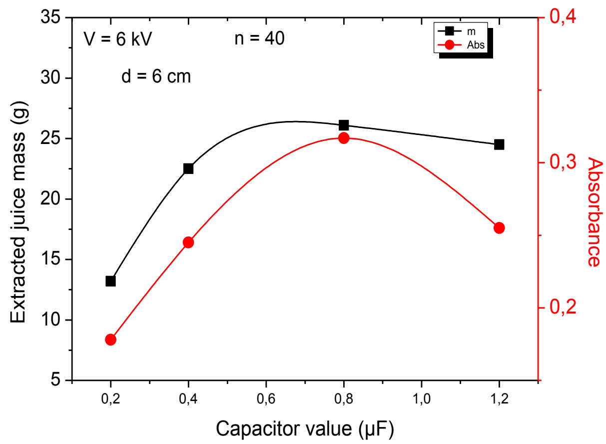


Fig 9. Evolution of the extracted juice mass (m) and Absorbance (Abs) according to the Capacitor value C for the different TC_1 model

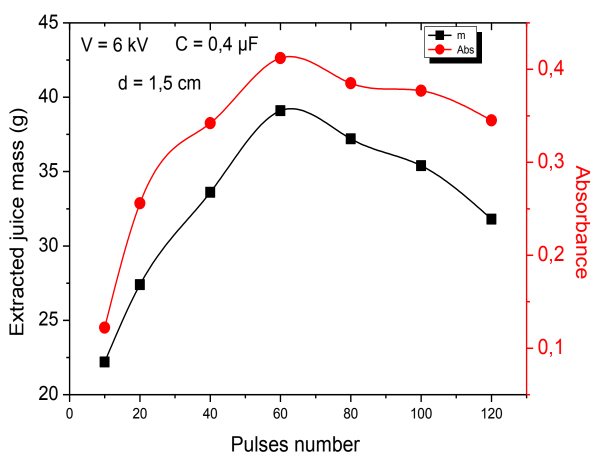


Fig 10. Evolution of the extracted juice mass (m) and Absorbance (Abs) according to the pulses number n for the different TC_2 model

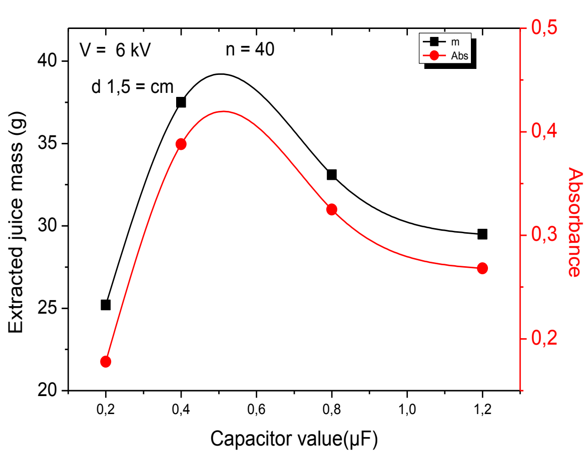


Fig 11. Evolution of the extracted juice mass (m) and Absorbance (Abs) according to the Capacitor value C for the different TC_2 model

Initial results shown that, the mass of extracted juice and the quantity of betanin obtained with a PEF-treated sample increases according to the pulses number and capacitor value respectively (Figures 8-11), for all models of treatment chambers. Further efficiencies may be obtained by using TC_2 treatment chambers model compared with the TC_1. The PEF efficiency can be minimized if the application of pulses number or capacitor value exceeds a determined value, the effect of the PEF treatment is inversed due to an excess energy provided to the product, which causes the opposite effect.

The effectiveness of the treatment chamber TC_2 compared to the model TC_1 returns to smaller pulses number and capacitor value applied to give a maximum of juice yield and betanin concentration compared with higher pulses number and important capacitor value in TC_1.

It should be noted that, the structure of the treatment chamber TC_2 comprises four food treatment compartments with a distance between electrodes of 1.5 cm from each compared to the model TC_1 then allows to treat a large mass of beet.

3.1. Design of PEF Treatment Experiments

Design of methodology for experiments is useful for screening, optimization [18]. Screening experiments are designed to identify the variation of the mass of extracted beet juice and absorbance depending to the two factors of treatment namely the pulses number (n) and the capacitor value (C) with the same applied voltage witch keep constant during PEP treatment, in order to determine a mathematical model of the juice mass with pulsed electric field (PEF) by using a dedicated modeling software MODDE 5.0 [19].

The study intervals for the various factors were chosen according to the responses obtained from the preliminary tests (figures 8-11).

Thus, the graph in figures 8 and 10 show that in the conditions of Experiment 1, the mass of extracted juice and absorbance increase up to 100 for TC1 and 60 for TC_2 respectively, and then decrease for higher values of pulses number.

Thus, nmin = 80 and nmax = 120 for TC_1 and nmin = 40 and nmax = 80 for TC_2 were retained as the limit values for the pulses number.

In the conditions of Experiment 2 shown in figures 9 and 11), we noticed the same variation concerning the influence of capacitor value. The mass of extracted juice firstly increased with the capacitor value up to C =0.8 μF for TC_1 and C= 0.4 μF for TC_2, then it decreased. Consequently, the domain of variation of this factor was

defined as Cmin = 0.4 µF and Cmax = 1.2 µF for TC_1 and Cmin = 0.2 µF and Cmax = 0.8 µF for TC_2.
The results of all the experiments are given in Tables 1 and 2.

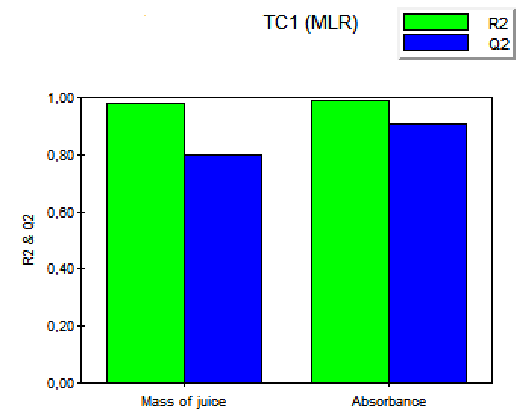
Table 1. Results of the CCF design experiment of TC_1

Exp N°	*n*	*C (µF)*	*m (g)*	*Abs*
01	80	0,4	21,3	0,302
02	120	0,4	28,2	0,384
03	80	1,2	24,7	0,364
04	120	1,2	30,3	0,395
05	80	0,8	27,4	0,389
06	120	0,8	32,7	0,457
07	100	0,4	28,5	0,327
08	100	1,2	32,8	0,383
09	100	0,8	34,3	0,42
10	100	0,8	34,3	0,42
11	100	0,8	34,3	0,42

Table 2. Results of the CCF design experiment of TC_2

Exp N°	*n*	*C (µF)*	*m (g)*	*Abs*
01	80	0,4	34,3	0,376
02	120	0,4	39,1	0,482
03	80	1,2	36,2	0,456
04	120	1,2	39,5	0,515
05	80	0,8	38,4	0,488
06	120	0,8	40,1	0,522
07	100	0,4	39,2	0,492
08	100	1,2	39,5	0,495
09	100	0,8	37,7	0,474
10	100	0,8	41,5	0,543
11	100	0,8	35,9	0,404

The predictive qualities of the models are satisfactory for both treatment chambers since the coefficient values Q^2 and R^2 close to 100%, (R^2 = 0.98, Q^2 = 0.80 for juice extracted and R^2 = 0.99, Q^2 = 0.90 for absorbance) for TC_1 and (R^2 = 0.99, Q^2 = 0.90 for juice extracted and R^2 = 0.98, Q^2 = 0.82 for absorbance) for TC_2 lead to a validated mathematical models (figure 12).



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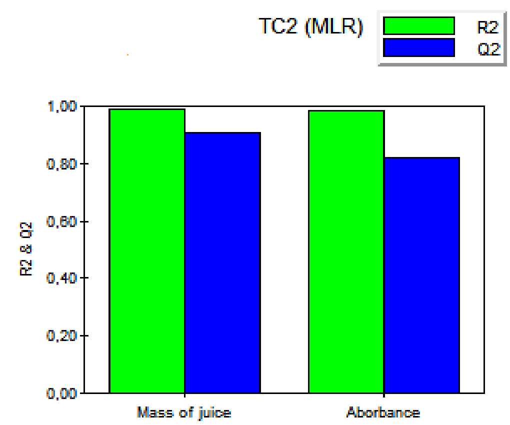
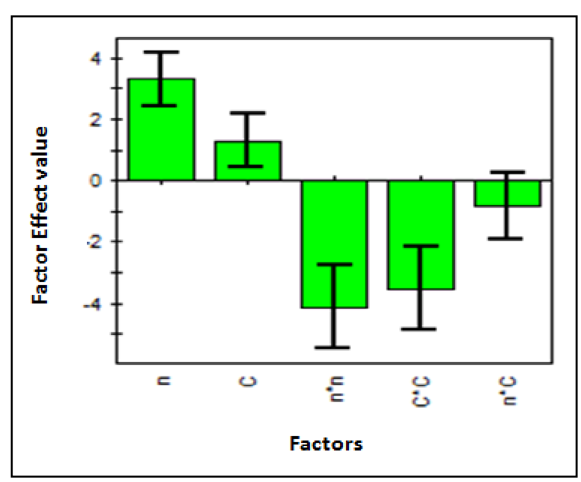


b)

Fig 12. Representation of descriptive quality and predictive quality of mathematical model for juice extraction and the absorbance for: a) TC_1, b) TC_2

MODDE 5.0 also gives the effect of each parameter on mass and absorbance extracted juice (figures 13 and 14).



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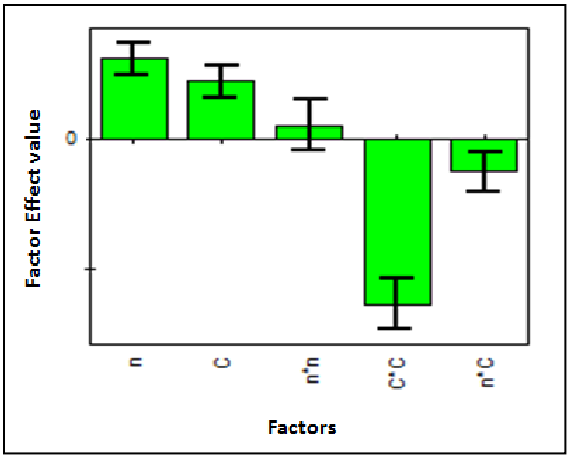
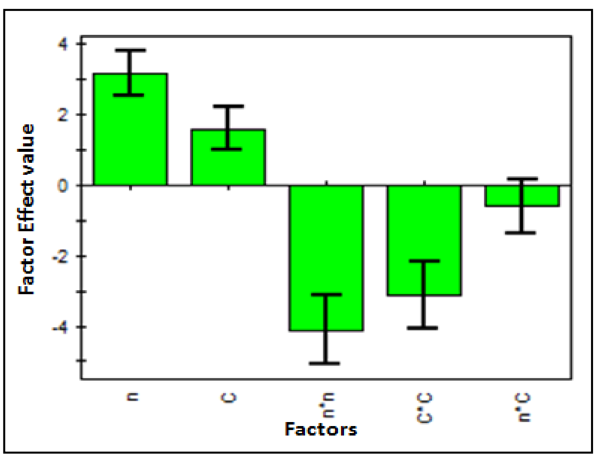


b)

Fig 13 . Plotted coefficients of the obtained model of TC_1 treatment chamber
a) Masse of extracted juice, b) Absorbance



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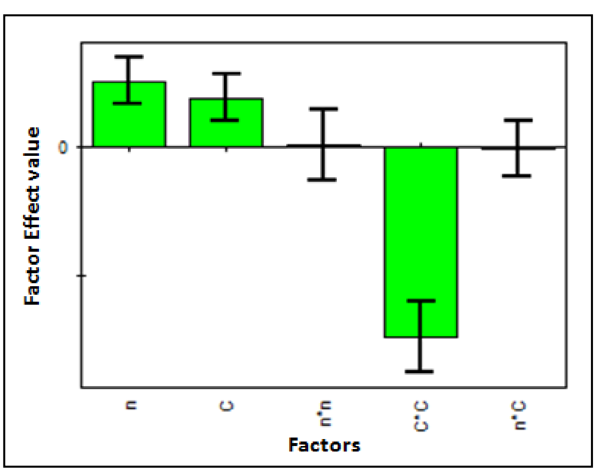

b)

Fig 14 . Plotted coefficients of the obtained model of TC_2 treatment chamber
a) Masse of extracted juice, b) Absorbance

According to the mathematical model obtained, the mass of the extracted juice and the absorbance should be higher by increasing both the pulses number n and the capacitor value for both chambers, the most significant factor being n. Moreover, the interaction between the pulses number and the capacitor value are not significant.

The mass of extracted juice m and absorbance Abs are the responses of the experimental design; the mathematical models for both treatment chambers were obtained as follows:

Table 3. Mathematical model of the responses for each TC

	TC_1		TC_2	
	Mass (g)	**Abs**	**Mass (g)**	**Abs**
Const	31,25	0.382	37,34	0,55
n	3,3	0.020	3,16	0,025
C	1,3	-0.00	1,6	0,019
n*n	-4,13	0.01	-4,10	0,001
C*C	-3,53	0.02	-3,10	-0,073
n*C	-0,82	-0.01	-0,60	-0,025

In addition, the software offers the possibility to identify the optimal values of the factors which should give the highest amount of mass (m) and absorbance (Abs) of extracted juice. According to this model, the optimum of the process (i.e., the greatest amount of beet juice) should be obtained for each TC model as shown in table.4 and figure.15.

Table.4. The optimum values obtained with MODDE.05 for both TC

	Mass (g)	**Abs**	**n** Optimal	**C** Optimal **(µF)**
TC_1	31.27	0.447	116	0.83
TC_2	37.14	0.574	77	0.54

	Factor	Response	Criteria	Weight	Min	Target
1	Pulses number	Mass of juice	Maximize	1	33,7022	35,0136
2	Capacitor value	Absorbance	Maximize	1	0,446299	0,462087

Iteration: 5001 Iteration slider:

	1	2	3	4	5	6
	Pulses number	Capacitor value	Mass of juice	Absorbance	iter	log(D)
1	115,996	0,8357	31,2781	0,447	5001	0,6547
2	115,995	0,836	31,2783	0,447	5000	0,6547
3	115,996	0,8357	31,2781	0,447	5001	0,6547
4	115,992	0,8358	31,2788	0,447	5000	0,6546
5	115,989	0,836	31,2794	0,4469	5001	0,6546
6	115,993	0,8359	31,2786	0,447	5001	0,6547
7	115,989	0,836	31,2794	0,4469	5001	0,6546
8	115,989	0,836	31,2794	0,4469	5001	0,6546

a)

	Factor		Response	Criteria	Weight	Min	Target
1	Pulses number	1	Mass of juice	Maximize	1	36,7132	37,971
2	Capacitor value	2	Aborbance	Maximize	1	0,570413	0,584885

Iteration: 5003 Iteration slider:

	1	2	3	4	5	6
	Pulses number	Capacitor value	Mass of juice	Aborbance	iter	log(D)
1	77,1563	0,5461	37,1311	0,5749	5001	-0,3367
2	77,0811	0,5388	37,1409	0,5748	5002	-0,3388
3	77,0822	0,5469	37,1461	0,5748	5000	-0,3391
4	77,1277	0,5422	37,1346	0,5749	5003	-0,3381
5	77,157	0,5479	37,1317	0,5749	5000	-0,3359
6	77,1106	0,5439	37,139	0,5749	5001	-0,3388
7	77,157	0,5479	37,1317	0,5749	5000	-0,3359
8	77,157	0,5479	37,1317	0,5749	5000	-0,3359

b)

Fig15. Subroutine of MODDE.05 representing the set point a) TC_1, b) TC_2

The obtained results show that the second model with five electrodes is more efficient, because better results in terms of juice mass and absorbance were obtained. This is explained by the increase of strength and the number of field lines for the model TC_2, thus the food product is exposed to more electric field lines than the simple configuration of the model TC_1.

3.2. Energy consumption

The energy consumed during treatment by pulsed electric field. This parameter was considered significant to be considered as the response of the model.

The energy consumed during treatment by pulsed electric field is calculated by relationship follows:

$$W = \frac{1}{2} nCV^2 \qquad (1$$

With:
n: pulses number
C : capacitor value (µF)
V : applied voltage (kV)
W : Energy consumed (Joule)

So, figure 16 represents the energy consumed during treatment by pulsed electric field with optimal values for both treatment chamber (TC_1 and TC_2).

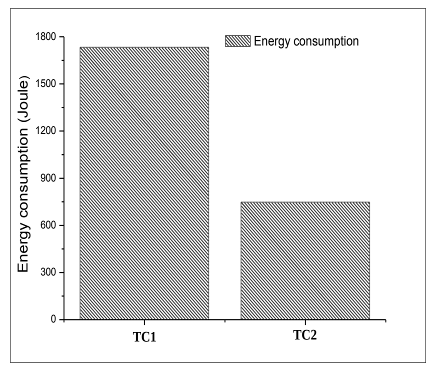

Fig 16. Energy consumption with optimal values for both treatment chambers TC_1 and TC_2

On the other hand, an energy saving more of 54 % was achieved for model TC_2 compared with the energy of the classic model TC_1.

4. Conclusion

Pulsed electric field technology is a multi factorial process which depends on several factors such as: electric field intensity, number of pulses and the capacitor value used in the treatment. In addition to all that, the treatment chamber configuration also has an important effect in the efficiency of this process.

This investigation describes an experimental comparative analysis between two square treatment chambers of same dimensions but having either two or five metal electrodes placed on the side walls. The experimental analysis was made by measuring the mass of PEF pre-treated extracted juice from beet and the amount of betanine using a spectrophotometer. The obtained results, using the methodology of experimental designs, have shown that the second model TC_2 with five electrodes is more efficient, because higher quantities of juice and betanine were obtained.

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