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ANALYSIS AND OPTIMIZATION OF PULSED ELECTRIC FIELD DISTRIBUTION EFFICIENCY IN A CYLINDRICAL TREATMENT CHAMBER FOR JUICE EXTRACTION

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ABSTRACT
Pulsed electric fields (PEF) technology has been receiving wide attention. The PEF treatment has the ability to trigger functional modifications in biological cells, without irreversible disruption of the cell membranes. Indeed, this process depends on several parameters such as the strength, pulses number and pulse duration of pulsed electric field (PEF). However, the influence of pulsed electric field distribution is also one of the key components in the PEF treatment process. The aim of this study 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. This parameter was studied by using the different cylindrical treatment chambers built in laboratory. The experiments were carried out on a laboratory experimental bench and the obtained results are very important not only in juice extraction yield, but for quality of final product.

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 minimizing sensory and nutritional damage, thus providing fresh-like products (Alirezalu *et al.,* 2019; Bobinaitė *et al.,* 2015; Zhang *et al.,* 1995). 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 (Pillet *et al.,* 2016). PEF processing has been successfully used for variety of liquids and pumpable food products such as orange and cranberry juices (Buckow et al., 2013; Dróżdż *et al.,* 2019), and apple juice and cider (Evrendilek *et al.,* 2002; Turk *et al.,* 2012; Xiufang *et al.,* 2013) without any loss of their natural characteristics. It has also been successfully used in enhancing juice extraction from apple, sugar beet, and alfalfa Agcam *et al.,* 2014; Gachovska *et al.,* 2006; Korma *et al.,* 2016; Yeom *et al.,* 2000).

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 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 (Rodrigo et al., 2001). The pores may close again after times which could last hours (Timmerman et al., 2014) or the damage may, at very high fields, become irreparable, and cell death occurs mainly used in bacteriological inactivation treatment (Jemai *et al.,* 2006; Anselmo *et al.,* 2015).

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 in order to better treat the food. The main objective of this work is to show that it is possible to give more juice by a better electric field distribution inside the treatment chamber with a good quality of betanine 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 modeling and optimization (Bellebna *et al.,* 2017; Bermaki *et al.,* 2017).

2. Materials and methods

Fresh beet stems, each of average mass 50 g were obtained at the 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.

Three cylindrical treatment chambers of different configurations were used in this study, all of which are made of an external electrode of 8 cm in diameter each and differ in terms of the internal electrodes and the gap between the electrodes. The first configuration consists of two concentric cylindrical electrodes (Con1external electrode connected to the ground, an internal electrode of 6 cm diameter connected to the high voltage and a gap between the electrodes of 1 cm (Figure.1). The second configuration is constituted also of two concentric cylindrical electrodes (Con2) an external electrode connected to the ground, an internal electrode connected to the high voltage of 4 cm diameter and a gap between the electrodes of 2 cm (Figure.2). The third configuration is constituted of the same external electrode connected to the ground while the internal electrode connected to the high voltage of 2 cm diameter and a gap between the electrodes of 3 cm (Con3) (Figure.3). In order to increase the processing capacity and provide an intense electric field for a more effective treatment.

After PEF treatment, an extraction step was achieved using an extraction chamber and a hydraulic pressing machine (Mega, 15 tons, Spain).

The chamber for extraction consisted of an insulated cylinder made of plastic (Teflon, PTFE) of length 140 mm and diameter 70 mm (Figure.4), a cylindrical plunger and a disc base of a same diameter 70 mm having a rigid structure for 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 this chamber. The volume of the treatment chamber was 192.3 ml. For all experiments, the same treatment chamber was used for both pressing step.

The pressure was applied using a hydraulic pressing machine (Mega, 15 tons, according to its labelling). Just after PEF treatment, the filled treatment chamber was pressed until a defined pressure of 50 kg/cm^2 and was then held at this pressure for 5 min.

The PEF treated extracted juice was then analyzed by measuring both its mass using an electronic balance of 0.1 mg precision and the betanine concentration by measuring the absorbance of beet juice using a spectrophotometer (Optizen 200 plus,Mecasys Co., Ltd) at λ= 530 nm.

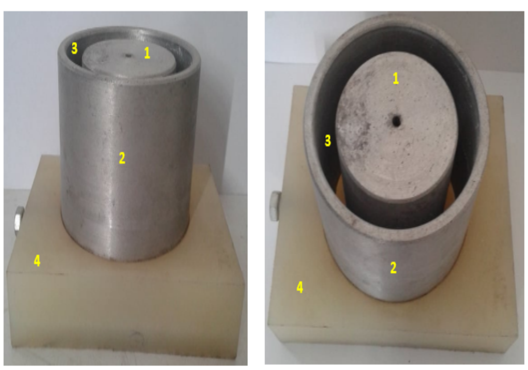


Figure 1. First configuration concentric cylindrical treatment chamber (Con1)
1. Internal electrode, 2. External electrode, 3. Gap between the electrodes, 4. The basis of the treatment chamber

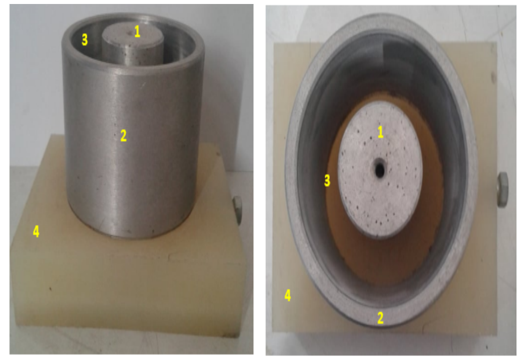


Figure 2. Second configuration concentric cylindrical treatment chamber (Con2)
1. Internal electrode, 2. External electrode, 3. Gap between the electrodes, 4. The basis of the treatment chamber

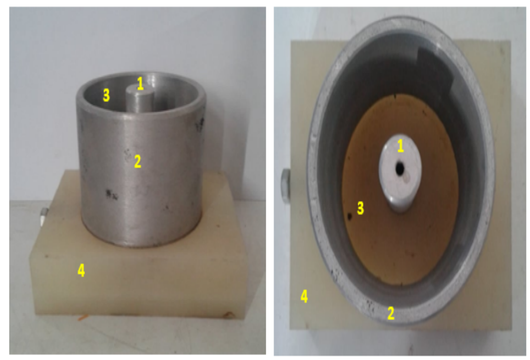


Figure 3. Third configuration concentric cylindrical treatment chamber (Con3)
1. Internal electrode, 2. External electrode, 3. Gap between the electrodes, 4. The basis of the treatment chamber

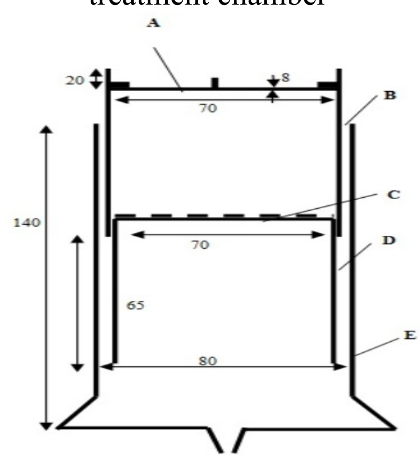
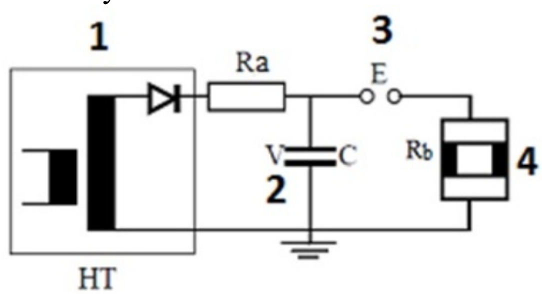


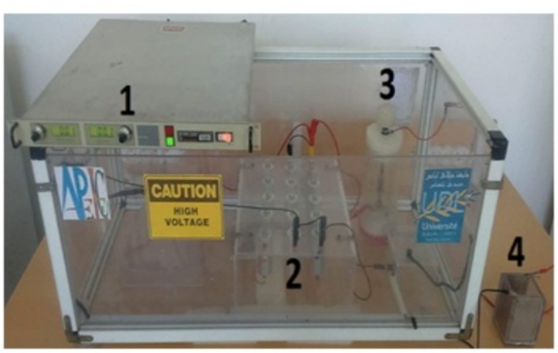
Figure 4. Schematic description of the chamber for extraction step (All dimensions are in mm).
A-Stainless Steel disk, B – Teflon cylinder, C – Stainless steel sieve, D -Perforated stainless steel plunger, E- Plastic container for the collection of extracted juice
(Bellebna *et al.,* 2017)

The pulse generator provides electrical exponential decay shape pulses of the desired voltage, and duration. The DC power supply (1) charges the capacitors bank (2) to the determined voltage. Using this device, the AC power from the utility line 50 Hz, is converted in alternating current (AC) high voltage power and then rectified to a DC high voltage power (figure 5). The energy provided by the DC power supply is temporarily stored in the capacitor(s) and then delivered very quickly in form of pulses to the treatment chamber by using the stainless steel spheres of the spark gap discharger of 15 mm in diameter, to generate the necessary electric field strength (figure 5).

A variable autotransformer (AT) (Langlois ALT5A) was used to supply the voltage to the circuit. The input voltage was regulated by the variable autotransformer (AT) to obtain a pulse frequency of 1 Hz, which was kept constant for all the study.



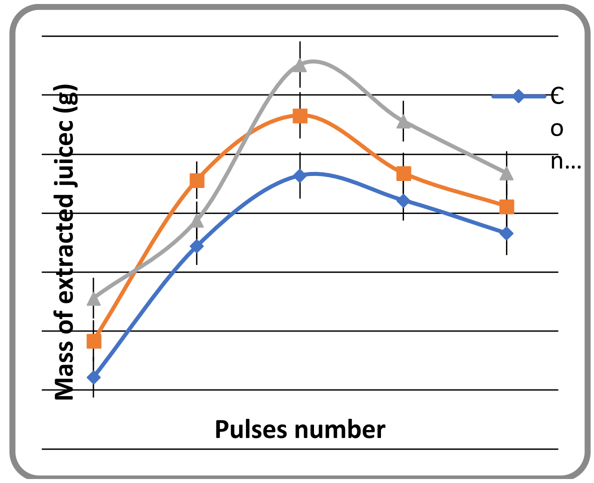
(a)



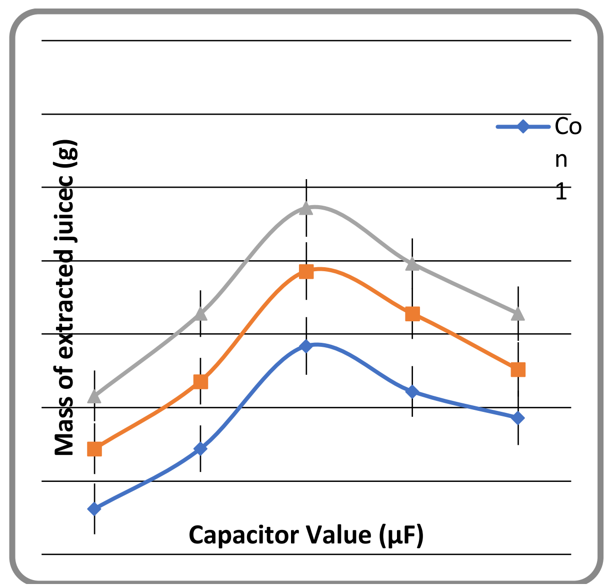
(b)

Figure 5. 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-Spark gap switch, 4-Treatment chamber

3. Results and discussions

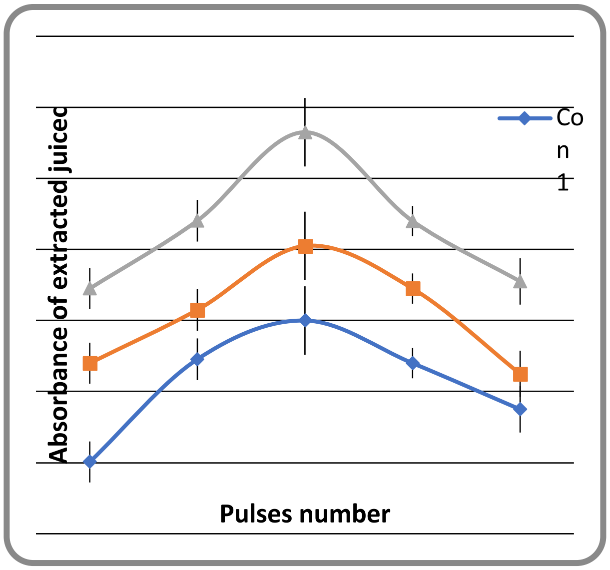


a)

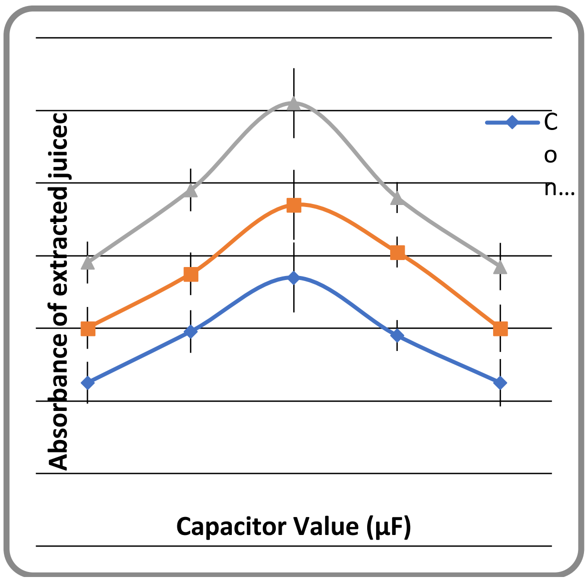


b)

Figure 6. Mass of beet juice extracted for different treatment chamber configuration according to
a) Pulses number (E = 2 kV/cm, C = 0.4 µF),
b) Capacitor value (E = 2 kV/cm, n = 60)



a)



b)

Figure.7. Absorbance of beet juice extracted for different treatment chamber configuration according to
a) Pulses number ($E = 2$ kV/cm, $C = 0.4$ µF),
b) Capacitor value ($E = 2$ kV/cm, $n = 60$)

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, figure 6 represent the variation of the PEF treatment efficiency, in terms of extracted juice mass (m), according to the pulses number n and the capacitor value C respectively from the same intensity of electric field, which was kept constant for all the study of 2 kV/cm. In order, the electric field depended of input voltage and distance between the electrodes.

In the same way, in Figure.7, is represented the evolution of the absorbance (Abs) as function of n and C respectively.

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 (Figures 6 and Figure 7), for all models of treatment chambers. Further efficiencies may be obtained by using Con3 treatment chambers model compared with the Con1 and Con2.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.

When the diameter of the electrode of the high voltage is low the electric field became more intense due to the dissymmetry in the electrodes of the treatment chamber which makes it possible to penetrate the electric field lines in the deep layers of the tissue to be treated leads to an effective treatment by pulsed electric field.

As well as the yield of extracted juice is significant, this distribution of the electric field gives the possibility of treatment of a large mass because the distance offered by this configuration of the treatment chamber is greater.

Increasingly the diameter of the active electrode increases the juice yield decreases. This is because pulsed electric field lines have become unable to penetrate deeply into the tissue of the food and only treat the surface of food because the electric field in this case has become lower with a quasi-uniform distribution.

The electroporation process is more efficient in Con3 compared with the order treatment chambers

3.1. Experimental designs methodology

Methodology of the experimental designs makes it possible to determine the number of experiments to be achieved according to a well defined objective, to study several factors simultaneously, to reduce dispersion related to measurements, to appreciate the effects of coupling between factors and finally to evaluate the respective influence of the factors and their interactions son

The Composite Centred Faces design (CCF), which gives quadratic models, was adopted. A quadratic dependence is established between the output function to optimize (response) and the input variables (Cheng *et al.,* 2016; Moradi *et al.,* 2016; Swamy *et al.*, 2014).

MODDE 5.0 software (Umetrics AB, Umea, Sweden) was used, which is a Windows program for the creation and the evaluation of experimental designs (MODDE 5.0., 1999).

The three following factors are studied:

1. Number of pulses n;
2. Capacitor value C (μF);
3. Treatment chamber Configuration (Coni) models are defined by 1, 2 and 3 for Con1, Con2 and Con3 respectively.

Indeed, Obtain results in previous section served to the definition of the domain of variation of n, C and Con_i. Thus, n_{min} = 40 and n_{max} = 80 were retained as the limit values for pulses number.

In the same for capacitor value, the domain of variation was chosen as C_{min} = 0.4 μF and C_{max} =1.2 μF. Indeed, we opted for the treatment chamber configuration model as Con_{min}= 1 and Con_{max}= 3 as limits of variation domain of Con.

The results of all the experiments are given in Table 1 and Figures 8 - 11 served to define the domain of variation of n, C and Con to indentify a mathematical model using MODDE 5.0 software.

According to all of the experiments, modeling software MODDE 5.0 gave us a mathematical model of juice extraction and absorbance using pulsed electric field treatment. This mathematical model is very satisfactory because the coefficients R^2 and Q^2 are very close to 1(figure 8). MODDE 5.0 also gives the effect of each parameter on extracted juice yield and absorbance value (figure 9).

Table 1. Results juice mass and absorbance experience extract according to variation in treatment values

Exp No	***n***	***C* [μF]**	***Con***	***Masse of juice* [g]**	***Absorbance***
1	40	0.4	1	23.3	0.831
2	80	0.4	1	26.4	1.087
3	40	1.2	1	31.8	1.015
4	80	1.2	1	31.7	0.51
5	40	0.4	3	33.7	0.288
6	80	0.4	3	42.3	0.377
7	40	1.2	3	37.3	1.01
8	80	1.2	3	40.4	0.32
9	40	0.8	2	30.7	0.796
10	80	0.8	2	33.1	0.514
11	60	0.4	2	37.5	0.439
12	60	12	2	37.1	0.421
13	60	0.8	1	33	1.149
14	60	0.8	3	41	0.565
15	60	0.8	2	37.2	0.503
16	60	0.8	2	37.2	0.503
17	60	0.8	2	37.2	0.503

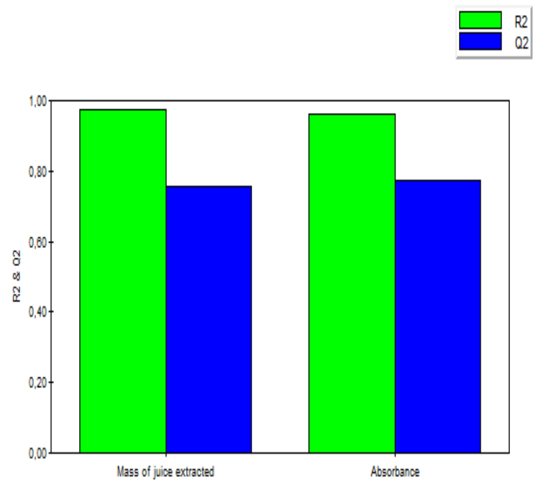


Figure 8. Representation of descriptive quality and predictive quality of mathematical model of juice extraction and absorbance

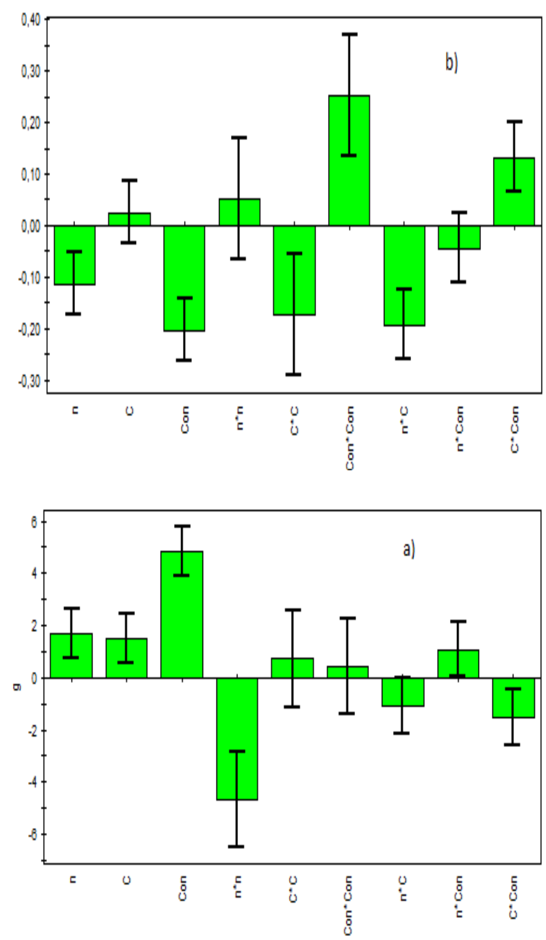


Figure 9. Values of the influence of each factor and their interactions
a) Mass of juice extracted, b) Absorbance

The predictive qualities of the model are satisfactory since the coefficient values Q^2 and R^2 close to 100% (R^2 = 0.97, Q^2 = 0.76 for juice extracted and R^2 = 0.97, Q^2 = 0.78 for absorbance) lead to a validated mathematical model (figure 8).

The mass of extracted juice M and absorbance ABS are the responses of the experimental design; the mathematical models were obtained as follows:

$$M = 36,84 + 1.71\, n^{*} + 1.51\, C^{*} + 4.85\, Con^{*} - 4.68\, n^{*2} - 1.08\, n^{*}C^{*} + 1.08\, n^{*}Con^{*} - 1.51\, C^{*}\, Con^{*} \quad (1)$$

$$Abs = 0.560 - 0.11\, n^{*} - 0.2\, Con^{*} - 0.17\, C^{*2} + 0.25\, Con{*}2 - 0.19\, n^{*}\, C^{*} + 0.13\, C^{*}Con^{*} \quad (2)$$

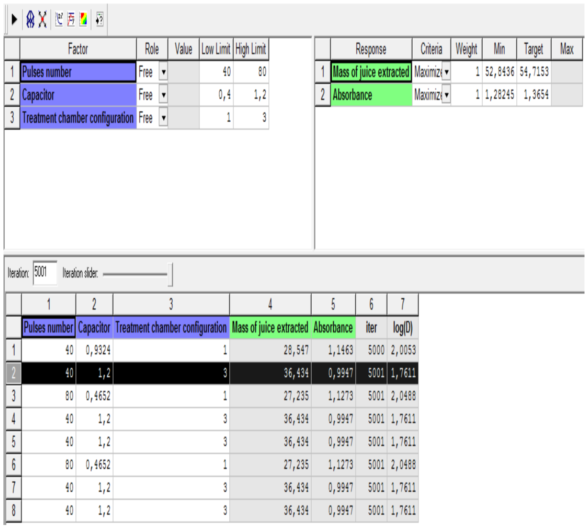
According to the mathematical model, the configuration of treatment chamber is the most important and influential factor in the mass yield of extracted juice and absorbance. This too is evident in these interactions with other factors.

The mass of the extracted juice should be higher by using the appropriate configuration of treatment chamber both the pulses number n and the capacitor value.

Moreover, except the interaction between the pulses number and the configuration with the capacitor value, other interactions are not significant. This means that the delivered energy during one pulse has an important effect on the electroporation process (figure.9-a).

On the other hand, the configuration of the treatment chamber has a negative influence on the absorbance that is explained that the absorbance decreases while increasing the amount of extracted juice (figure.9-b).

According to this model, the optimum of the process (i.e., the greatest amount of beet juice and absorbance) should be obtained for number of pulses n0 = 40, capacitor value C_0 = 1.2 µF and with using of the third treatment chamber configuration Con = 3 (figure 10).



	Factor	Role	Value	Low Limit	High Limit
1	Pulses number	Free		40	80
2	Capacitor	Free		0,4	1,2
3	Treatment chamber configuration	Free		1	3

	Response	Criteria	Weight	Min	Target	Max
1	Mass of juice extracted	Maximize	1	52,8436	54,7153	
2	Absorbance	Maximize	1	1,28245	1,3654	

Iteration: 5001 Iteration slider:

	1	2	3	4	5	6	7
	Pulses number	Capacitor	Treatment chamber configuration	Mass of juice extracted	Absorbance	iter	log(D)
1	40	0,9324	1	28,547	1,1463	5000	2,0053
2	40	1,2	3	36,434	0,9947	5001	1,7611
3	80	0,4652	1	27,235	1,1273	5001	2,0488
4	40	1,2	3	36,434	0,9947	5001	1,7611
5	40	1,2	3	36,434	0,9947	5001	1,7611
6	80	0,4652	1	27,235	1,1273	5001	2,0488
7	40	1,2	3	36,434	0,9947	5001	1,7611
8	40	1,2	3	36,434	0,9947	5001	1,7611

Figure 10. Subroutine of MODDE.05 representing the set point

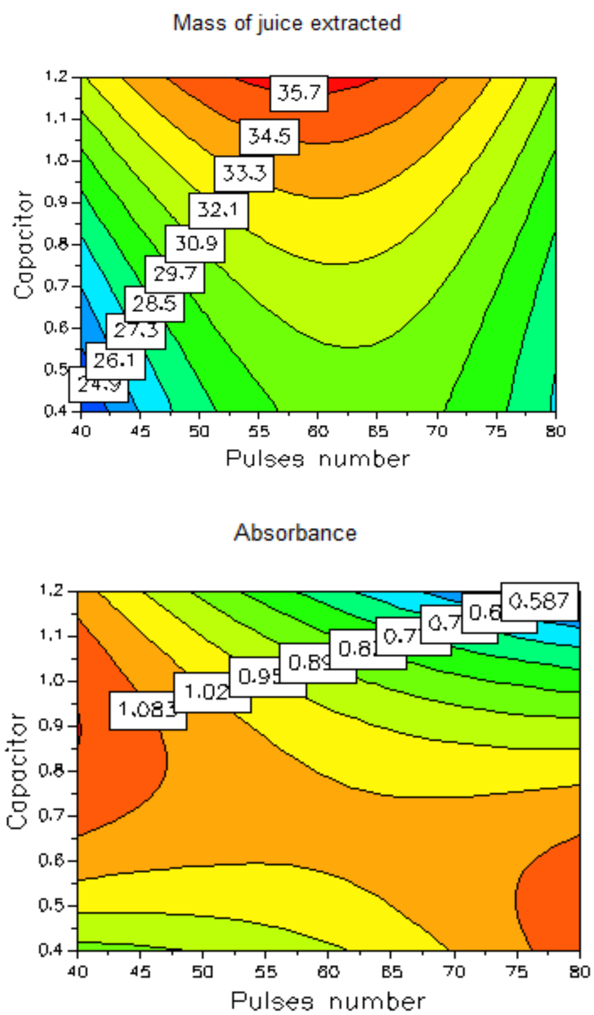


Figure. 11. Response contour plots of the masse of juice extracted and absorbance for Con1

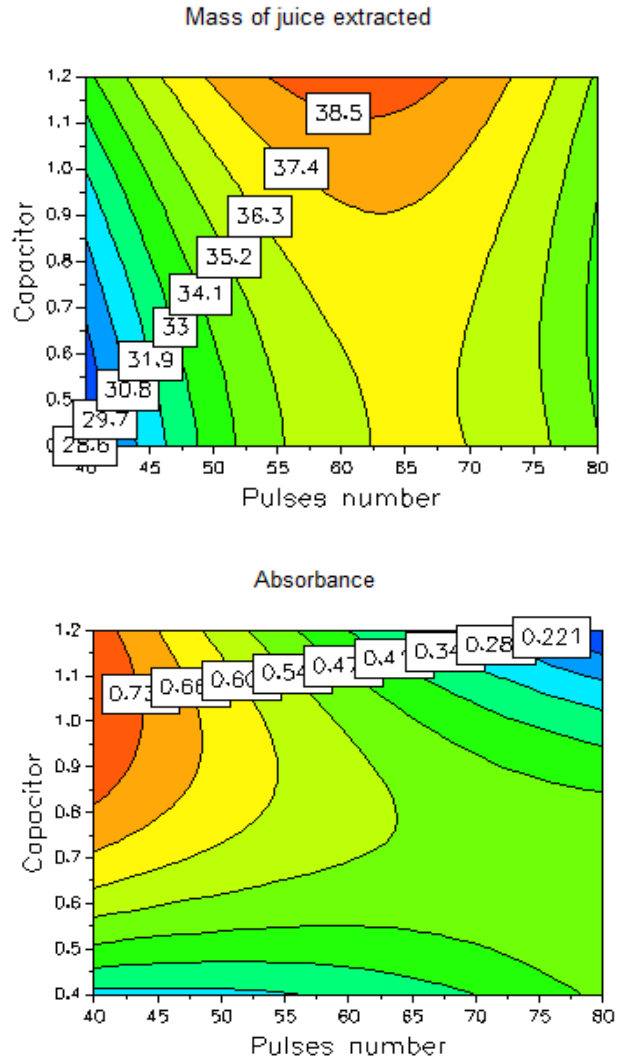
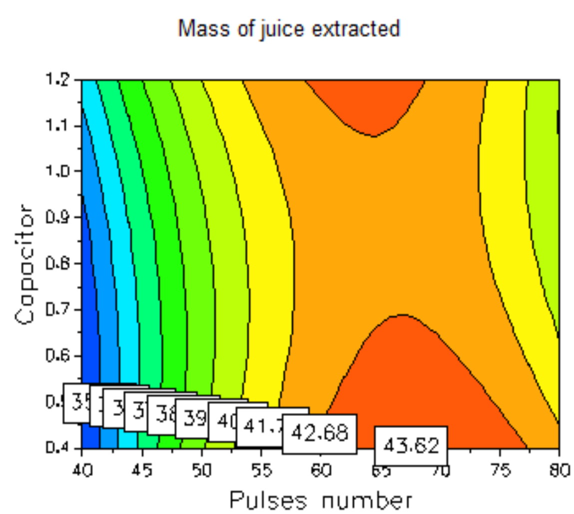


Figure. 12. Response contour plots of the masse of juice extracted and absorbance for Con2



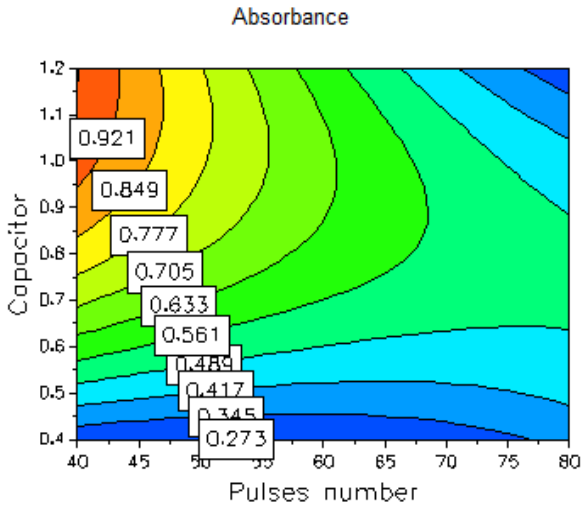


Figure. 13. Response contour plots of the masse of juice extracted and absorbance for Con3

4. Conclusions

In conclusion, results obtained in this investigation confirm that the applications of PEF treatments in the range of asymmetrical treatment chamber configurations are more effective in the enhancement of the beet juice extraction. However, treatments delivered in the range of treatment chambers of symmetrical or quasi-symmetrical treatment chamber configurations were more effective in the extraction of betanine.

Finally, in addition to the proper choice of the treatment chamber configuration the pulses number requirements and the capacitors value processing required for PEF process are also significant parameters for an effective treatment.

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