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REVIEW ARTICLE

OPTIMIZATION OF HYBRID SOLAR DRYING OF OKRA BY USING RESPONSE SURFACE PLANES

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ABSTRACT

In order to optimize solar drying, a study by surface plane of centered response composite types was used. After the choice of 3 factors, 16 experiments were carried out and led to a mathematical model of the second degree linking the responses (drying time and energy consumption) to the factors considered influential.After carrying out the experiments and analyzing the results using Minitab software, the study has allowed determined the optimal conditions needed to obtain a drying time and a minimum energy consumption to obtain a dry product with a water content of 15% in wet base. The analysis of the main effect profiles as well as the mathematical correlation show the following:

- energy consumption was proportional with the thickness of the slice, the temperature and the speed of the air;
- the drying time was proportional to the thickness of the slice and inversely proportional to the temperature (from the center of the domain to its upper level) and the air velocity;
- a good concordance between the selected models and the experimental results was observed with correlation factors of 99.3% and 99.8% respectively for drying time and energy consumption. The optimal values of drying time DS=318.2922 minutes and energy consumption CE=7.1859 kwh with an overall desirability of 90.29% were obtained with the following optimal operating conditions:
- Drying air temperature of 40°C;
- Product thickness of 11.5mm;
- Air velocity of 1.02m/s.

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INTRODUCTION

Okra is one of the most consumed vegetable fruits in Africa, due to its availability, nutritional qualities and medicinal properties.It is not very calorific, because matter 100g brings 36 kcal (Sawadogo et al.,2006).It is used in panification as agent texturant (Acquistucci and Francisci, 2002;Sharma et al.,2007), in medicine for the cicatrization of the internal lesions of stomach.It is also appreciated for nutritional, technological and economic reasons.It contains between 87 to 90% of water, 7 to 8%of glucides, vitamins A, B, K and E as well as rock salts (Hamon and Charrier, 1997). However, its strong water content returns its activity microbiological intense with like consequences the losses going up to 40 to 50% of its production.In period of harvest, the producers are confronted with a short-term overproduction and a difficulty of extending the conservation of this food product over all the year in the developing countries where the techniques of conservation are almost quasi-non-existent. Drying is the mode of conservation the most used for the conservation of the agroalimentary products because, it makes it possible to block the microbial activity by the reduction of the water content.It is though effective for the conservation of the products, this technique requires a great quantity of energy. However, this mode of drying presents multiple disadvantages:intermittent character of solar energy with impact a prolongation of the drying time , no the maitrise of the process leading to the bad quality the product.To cure these problems, we propose to use a hybrid solar drier in order to ensure the maitrise of the drying operation thus to have a product of better quality after its drying.Although effective for the conservation of the products, this technique requires a great quantity of energy, the deterioration of the nutritional quality of the product and to the prolongation of the drying time when it is not maitrisez. The optimization of drying converges towards the research of the optimum conditions for operation for the variables of the process which have like consequence best performance of drying in particular to reduce the time of drying and the power consumption.

He method of surface réponse(RSM) was proven like an effective tool to determine the effects of each factor and the existing interactions between them. This method is by definition a collection of the experimental strategies of the mathematical models and statistics which make it possible to the experimenter to choose best combinations the levels of the parameters which optimize the drying operation (Benseddik et al.,2016). The RSM is a faster and economic method for the collection of the research results. This study related to the optimization the solar drying of the sections gombo in particular on the reduction of time and the power consumption of drying.The objective is to find a mathematical model making it possible to optimize the drying operation of the gombo by rationalizing the power consumption and the time of drying for obtaining a dry gombo with a water content of conservation which is 15% in wet base.The experiments were conceived according to the composite plan centered reduite on three levels and three factors.

MATERIALS AND METHODS

Materials

Experimental material

Figure 1. Hybrid Solar Dryer

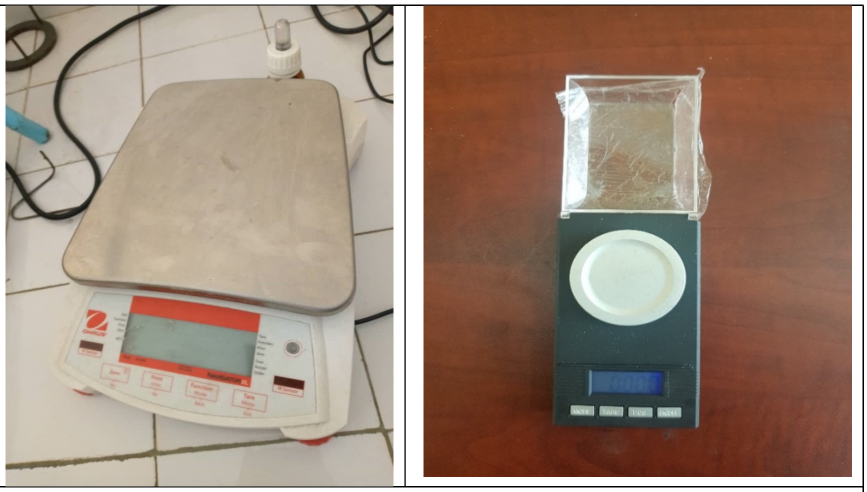

Figure 2. Balance with an accuracy of 0.001g

The experimental study on this dryer consists of the measurement:

- Global solar radiation received on the sensor plane using a polarimeter whose results are displayed digitally.
- Temperatures using thermo hydrometers at the input, output of the sensor and the ambient environment.
- Systematic weighing of dried products to be dried using a 0.001g precision scale.
- Record electrical energy consumption using a digitally displayed electricity meter in kWh.

Plant material: The vegetable material used is fresh Gombo *(Abelmoscus Esculentus*) bought at the market of the town of Brazzaville.

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Methods

Measurements made

The experimental study on this dryer consists of the measurement:

- Global solar radiation received on the sensor plane using a polarimeter whose results are displayed digitally.
- Temperatures using thermo hydrometers at the input, output of the sensor and the ambient environment.
- Systematic weighing of dried products to be dried using a 0.001g precision scale.
- Record electrical energy consumption using a digitally displayed electricity meter in kWh.

Wet base water content $X=\frac{M_0-M_s}{M_0}$;M_0: Wet base water content(g),
M_s:dry mass (g)

Experimental protocol: The experimental method consists in daily carrying out the drying of the product between 07h and 18h.Test were carried out during the time of the 2020/12/05 to the 2021/02/20 with the températures(40 °C, 50 °C, 60 °C), at speeds (1 m/s, 1.5 m/s, 2 m/s) and thicknesses of the gombo(10 mm, 15 mm and 20 mm). The experimental method consists in daily carrying out the drying of the product between 07h and 18h**.**Test were carried out during the time of the 2020/12/05 to the 2021/02/20 with the températures(40 °C, 50 °C, 60 °C), at speeds (1 m/s, 1.5 m/s, 2 m/s) and thicknesses of the gombo(10 mm, 15 mm and 20 mm). Followed loss of mass product during drying is ensured by taken measurements of mass with regular intervals of 30 minutes time by using a balance of exactitude of 0.001g. The end of the operation is marked by the stabilization of the mass of the product after three successive weighings. Temperature and solar radiation measurements are made every 30 minutes

Choice of parameters and ranges of variations: The objective assigned in this study of the experimental designs, is to find the point of optimal operation of the hybrid solar drier. The preliminary tests carried out as well as the work completed by the authors suchas Doymaz (2005), Seiidlou et al., (2010) and Ndukuwu (2009) show that the above mentioned factors have a considerable influence over the duration like on the power consumption of the drying of the agro-alimentary products.It is about the implementation of an experimental design of answers surface of the composite type centered reduite for the determination of the polynomial model of order 2 representative the duration of drying as well as the power consumption of a hybrid solar drier.A composite experimental design centered of 16 essais(K^2 +2.K+n_0) with a repetition in the center of the field of study was used to optimize the operation of drying and to study the influence of the operational parameters suchas the temperature of the drying air (40-60°C), the speed of dryingair (1-2 m/s) and the thickness of the samples of the gombo (10-20 mm) over the duration of drying as on the power consumption to have a product with a water content of 15% in wet base is an activity of conservation of 0.6;considered like water content of stabilization microbiologique (Sawadogo et al.,2016). The range of variation of each parameter consists of all values between the high level (+1) and the low level (-1). Once the experimental model is determined, it will therefore be possible to predict the minimum responses and optimization of the experimental conditions of the dryer. Table 1 shows the factors studied and their ranges of variation.

Table 1. Experimental areas of factors studied in drying optimization

Factors	symbol	Lower level(-1)	Higher Level(+1)
Air temperature	X_1	40°C	60°C
Product thickness	X_2	10mm	20mm
Air velocity	X_3	1m/s	2m/s

Responses studied : Two answers are studied in this work:

Drying time: For this work, the drying time corresponds to the time needed to reach a water content of 15% in wet base. This value is determined by simulation and extrapolation of the function X=f(t) using the Orginpro8, 2018 software.

Energy consumption during drying: The energy consumption was determined in order to achieve the product's conservation water content of 15% in wet base. This energy consumption represents the sum of heat provided by the solar collector and the electrical backup. This estimate is done by using the following relationship:

$CE=I_g t+E_R+E_V$(kwh)
I_gt : Solar energy entering the collector(kwh) for a time
E_R : Energy consumed by electrical resistors(kwh)
E_V : Energy consumed by the fan (kwh)
In the event that drying is carried out in the absence of the sun,
CE= E_R+E_V (kwh)

This value is determined by simulation and extrapolation of the function X=f(CE) using Orginpro8, 2018 software.

Mathematical model

The postulated mathematical model is a polynomial of order 2 such that the equation:

$$DS=b_0+b_1X_1+b_2.X_2+b_3X_3+b_{11}.X_1^2+b_{22}.X_2^2+b_{33}.X_3^2+b_{12}.X_1X_2+b_{13}.X_1X_3+b_{23}.X_2X_3+b_{123}.X_1X_2X_3+\epsilon \quad (1)$$

$$CE=b'_0+b'_1X_1+b'_2.X_2+b'_3X_3+b'_{11}.X_1^2+b'_{22}.X_2^2+b'_{33}.X_3^2+b'_{12}.X_1X_2+b'_{13}.X_1X_3+b'_{23}.X_2X_3+b'_{123}.X_1X_2X_3+\epsilon \quad (2)$$

and :
DS :is the drying time (min)
b_0*:is the theoretical mean value of the response*
b_1,b_2,b_3 *are coefficients of linear terms*
b_{11},b_{22},b_{33} *are coefficients of quadratic terms*
b_{12},b_{13},b_{23} *:Coefficients of interaction terms*
ϵ *: the error term*
CE :is energy consumption (kwh)
b'_0*: is the theoretical mean value of the response*
b'_1,b'_2,b'_3 *are coefficients of linear terms*
b'_{11},b'_{22},b'_{33} *are coefficients of quadratic terms*
b'_{12},b'_{13},b'_{23} *:Coefficients of interaction terms*
ϵ *: the error term*

Statistical analysis and optimization: Statistical analysis is used to validate the results of the modeling. The use of statistical tests is closely related to the knowledge of the standard deviation estimated by repeatability tests.These tests also make it possible to evaluate the quality of the model, its validation using the analysis of variance and the significance of the coefficients using the student test. The implementation of these tests also makes it possible to make a judgment on the results obtained, namely:

• The quality of the model is estimated using the coefficient of determination R^2. The quality of the model is considered satisfactory when the coefficient of determination is close to 1(100%). It is determined by the following formula. $R^2 = \frac{\sum_{i=1}^{N}(y_{i-y_i bar})^2}{\sum_{i=1}^{N}(y_{j-y_i bar})^2}$

Y_i : response from the model

Y_i : experimental or measured response

$Y_{i,bar}$:average of experimental responses.

•The t-student test was used to determine the statistical significance of the parameters. The coefficients of the model will be considered significant for p-value values<0.05.

RESULTS AND DISCUSSION

Experimental plan: The experimental plan of the composite plan centered on three levels and three factors with the values of the observed responses is listed in Table 2.

Table 2. Shows the experimental matrix of a composite response surface plane centered with the observed response values

	Factors			Answers	
N° Ordre	X1	X2	X3	CE (kwh)	DS (min)
1	0	0	+1	8.67	344.12
2	-1	0	0	8.17	350.32
3	0	0	-1	8.03	423.32
4	-1	+1	-1	7.69	450.82
5	+1	+1	-1	8,87	481.12
6	-1	-1	-1	7.17	316.72
7	0	-1	0	7.88	392.92
8	+1	-1	+1	9.35	281.82
9	0	+1	0	8.09	485.52
10	+1	0	0	9.29	341.12
11	+1	+1	+1	9.20	328.92
12	0	0	0	8.29	415.55
13	-1	-1	+1	8.20	319.52
14	+1	-1	-1	8.72	436.02
15	-1	+1	1	8.60	442.62
16	0	0	0	8.36	400.55

Statistical validation of the postulated model: The results shown in Table 3 indicate that the coefficient of determination R^2 shows that the model has a good fit and close to unity for both responses. This value indicates that there is a good agreement between the experimental data and the data predicted by the mathematical model. Each of these values was compared to the predicted values calculated from the model (Figure 3 and 4). The results indicate that the model used for both responses was able to identify the optimal drying operating state of okra. Figures 3 and 4 show a correlation between the experimental value and that predicted by the mathematical model.

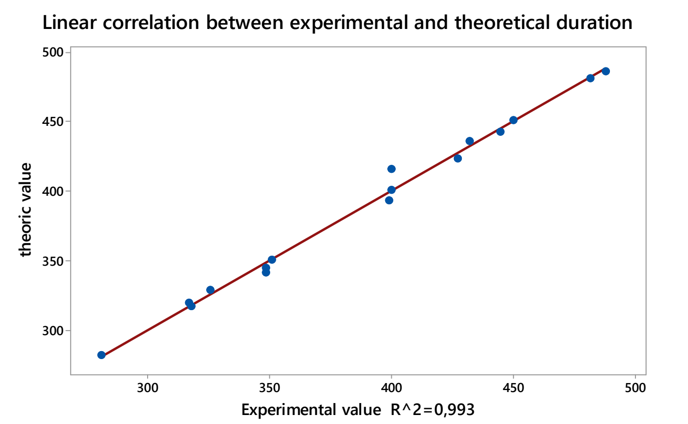

Figure 3: Corrélation entre la Valeur expérimentale et théorique pour la durée de séchage

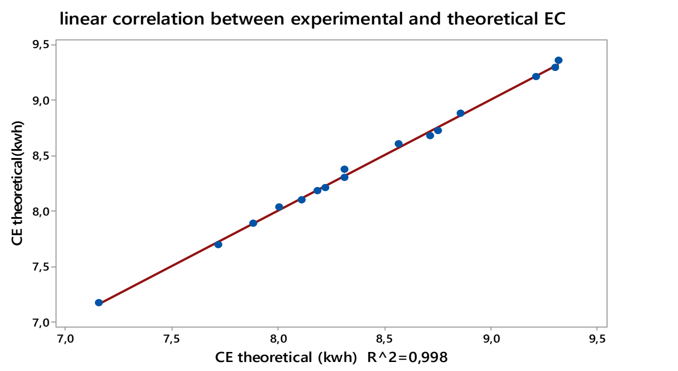

Figure 4. Corrélation entre la Valeur expérimentale et théorique pour la consommation énergétique

Model quality: The quality of the model is verified by comparing the standard deviation of the experimental error to that of the model residues. The variation analysis (ANOVA) in Table3, indicates that the drying time (DS) and energy consumption (DS) model support most of the explanation of the measured responses, with an average F-of-square ratio of 94.52 for duration and 328.08 for energy consumption that are sufficient to validate the model. The F ratio measures the probability that the variance explained by default is not different from the variance of pure error. A high probability therefore indicates that the fit defect is not statistically different from the experimental error, such is the case of our model with Pro>F(=0.767)>0.05 for drying time and Pro>F(=0.717) for energy consumption. The duration model of drying and energy consumption are therefore of good quality.

Table 3. Analysis of Variance (ANOVA) for the postulated model

Drying time					
spring	ddl	Sum of squares	Medium square	Report F	P-value
Regression	9	59265.0	6585.0	94.52	0.000
Residues	6	418.0	69.7		
Total	15	59683.0			
Pure error	1	112.5	112.5	0.54	0.767
Lack adjustment	5	305.5	61.1		
R^2		99.3%			
Energy consumption					
Regression	9	5.37516	0.59724	328.08	0.000
residues	6	0.01092	0.00182		
Total	15	5.38608			
Pure error	1	0.00245	0.00245	0.69	0.717
Lack adjustment	5	0.00847	0.00169		
R^2		99.8%			

Absence d'ajustement : The models resulting from quadratic regression for drying time and energy consumption are given by equations (eq.3) and (eq.4) respectively. Experimental data were used to calculate the coefficients of the quadratic equation using Minitab software and tables(3-5) summarize the results for the analysis of variance and the model coefficients for the two respective responses.

Table 4. Coefficients of the postulated mathematical model for the drying time

Drying time						
Terme	Coefficient	Estimate	Standard deviation	t-student	p-value	Judgement
Constant	b0	399.88	3.95	101.19	0.000	*significatif*
$\square_1$	b1	-1.10	2.64	-0.42	0.691	*Not significant*
$\square_2$	b2	44.20	2.64	16.75	0.000	*meaningful*
$\square_3$	b3	-39.10	2.64	-14.81	0.00	*meaningful*
$\square_1^2$	b11	-50.07	5.14	-9.74	0.000	*meaningful*
$\square_2^2$	b22	43.43	5.14	8.45	0.000	*meaningful*
$\square_3^2$	b33	-1.07	5.14	-2.35	0.057	*meaningful*
$\square_{12}$	b12	-20.62	2.95	-6.99	0.00	*meaningful*
$\square_{13}$	b13	-37.63	2.95	-12.75	0.000	*meaningful*
$\square_{23}$	b23	-1.13	2.95	-0.38	0.716	*Not significant*

Table 5. Coefficients of the postulated mathematical model for energy consumption

Energy consumption						
Term	Coefficient	Estimate	Standard deviation	t-student	p-value	Judgement
	b'0	8.3115	0.0202	411.47	0.000	meaningful
X_1	b'1	0.5593	0.0135	41.45	0.000	meaningful
X_2	b'2	0.1135	0.0135	8.42	0.000	meaningful
X_3	b'3	0.3539	0.0135	26.23	0.000	meaningful
X_1^2	b'11	0.4297	0.0263	16.23	0.033	meaningful
X_2^2	b'22	-0.3141	0.0263	-11.95	0.000	meaningful
X_3^2	b'33	0.0473	0.0263	1.80	0.122	Not significant
X_{12}	b12	-0.1137	0.0151	-7.54	0.000	meaningful
X_{13}	b13	-0.1234	0.0151	-8.18	0.00	meaningful
X_{23}	b23	-0.0542	0.0151	-3.59	0.011	meaningful

- The estimation of the coefficients of the drying time response (Table 4) shows that the terms X_2,X_3,X_1^2, X_2^2,X_3^2 ,X_1X_2,X_1X_3 are statistically significant over drying time because the P-value probability values are less than 0.05. However, the terms X_1,X_2X_3 of probability P-value are greater than 0.05 are significantly insignificant.On the basis of these results, an empirical model linking the drying time response and the terms considered significant is retained and given by the following equation:

$$DS(min)=399.88-1.10.X_1+44.2.X_2-39.10.X_3-50.07.X_1^2+43.43.X_2^2-12.07.X_3^2-20.62X_1X_2-37.63X_1X_3 \quad (eq.3)$$

- The estimation of the coefficients of the energy consumption response (Table 5) shows that the terms X_1,X_2,X_3,X_1^2,X_2^2, X_1X_2,X_1X_3 are statistically significant on energy consumption because P-value probability values are less than 0.05.However, the terms X_3^2 is significant because the probability value P-value is greater than 0.05.On the basis of these results, the mathematical model chosen for the energy consumption response is given by the following equation:

$$CE(kwh)=8.3115+0.5593.X_1+0.1135.X_2+0.3539.X_3+0.4297.X_1^2-0.3141.X_2^2-0.1137.X_1X_2-0.1234.X_1X_3-0.0542.X_2X_3 \quad (eq.4)$$

Parameter Optimization

Main effects: Figure 5 shows the main effects of factors on drying time. We find that when the temperature changes from 50°C à 60°Cthe drying time decreases from 400 min to 348 min. These results are in agreement with those found by authors such as Doymaz (2005) and Jiokap et al., (2021).This same observation is made with the speed of the air, the increase of which considerably reduces the drying time from 425 min to 324 min when it goes from 1m/s à 2m/s.However, the increase in the thickness of the product from 10mm to 20mm leads to an extension of the drying time from 437min to 398min; this extension can be explained by the increase in the distance traveled by the humidity between the center and the surface of the product d and the water migration constraints in the product that increase with the thickness of the product.This results are identical with the work of Nguyen,(2015) and Benseddik etal.,(2016). The figure highlights the main effects of operating factors on energy consumption.This figure tells us that the increase in these three factors leads to a significant increase in the energy consumption of drying.Indeed, the increase in temperature from 40 to 60 ° C increases the energy demand from 8.14 to 9.27kwh. Similarly, increasing the thickness of the product from 15mm to 20mm generates a high energy consumption of 8.12 to 8.37 kWh. These results are in line with those found in the literature by researchers such as Boughali,(2010) and Youssouf Kone,(2011). In addition,the increase in air velocity from 1m/s to 2m/s increases energy demand from 8 to 8.72kwh.Taking these results into account, obtaining a dry okra with a final water content of 15% therefore requires a low air temperature, a low thickness of the product and a more or less low air velocity possible.

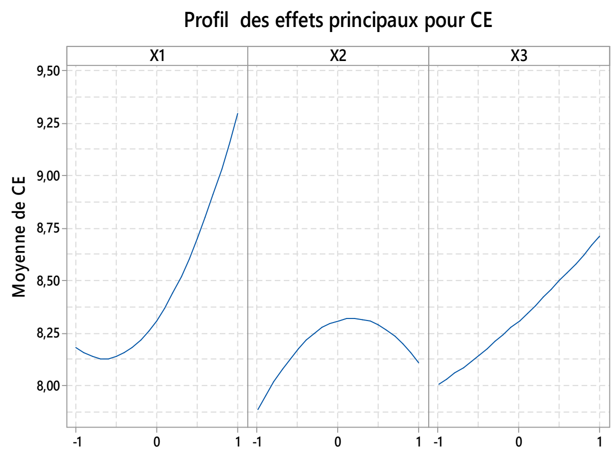

Figure 5: Profile of the main effects for energy consumption (kwh)

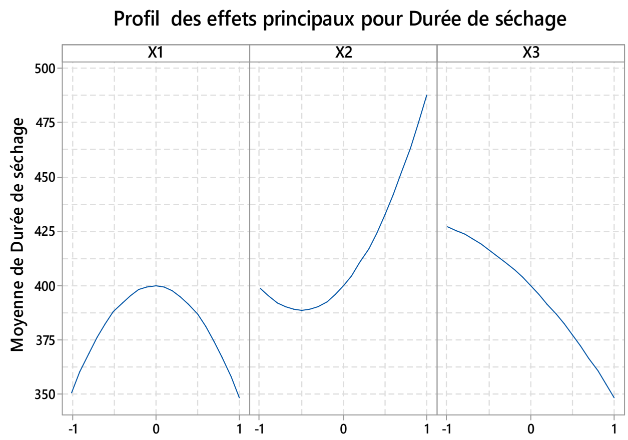

Figure 6: Profile of main effects for drying time (min)

Study of desirability: The objective of our study is to find a water content of microbiological stability of okra, corresponding to a water activity of 0.6 (or 15% in wet base), while minimizing the duration and energy consumption of drying. This water content was determined in the interior works by the authors such as Kemmene Dapabko et *al*., (2021). These results indicate that obtaining the desired humidity with a minimum duration requires an increase in the temperature towards the center of the variation range of this factor (50 ° C), an increase in the speed of the air towards its highest (2m / s) and a low thickness of the product (10mm) . Figure 7 shows that this water content can be achieved with an overall desirability of 90.29% by ensuring optimal operating conditions:

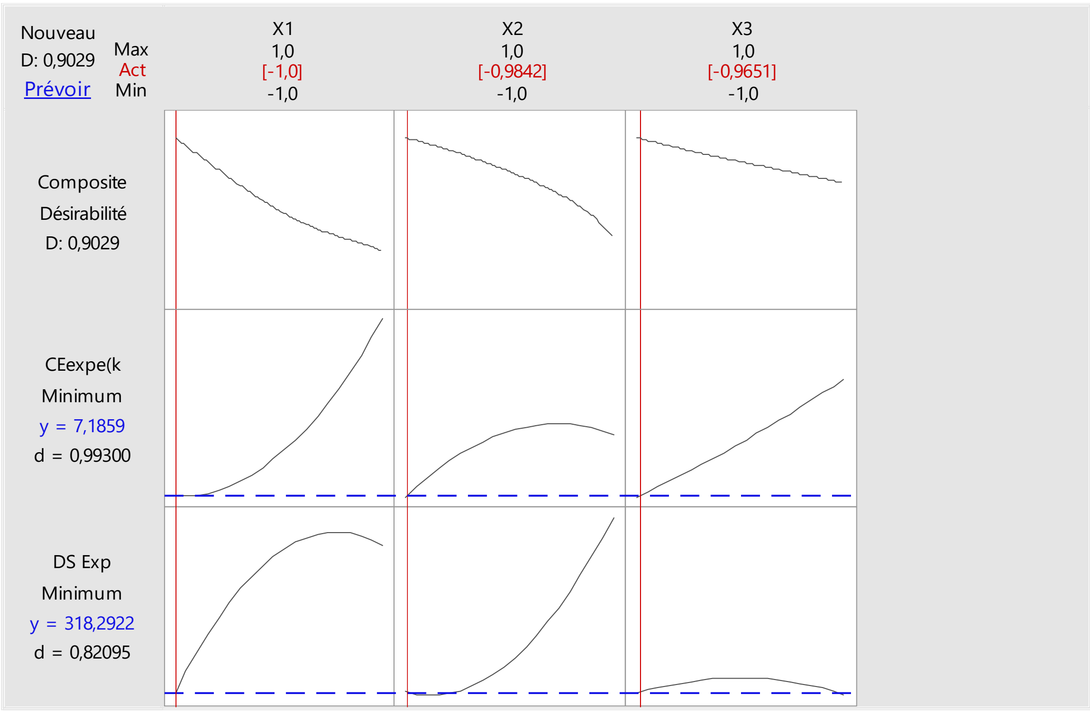

Figure 7. Prediction profile of optimal okra drying conditions

- Drying air temperature (X_1)=-1 in coded value, which corresponds to 40°C
- Product thickness (X_2) =-0.9842,which corresponds in coded value to 11.5mm.
- Air velocity (X_3)=-0.9651,ce qui correspond en valeur codée à 1.02m/s

CONCLUSION

The objective of this work is the modeling and optimization of the solar drying process of okra slices by the methodology of centered response surfaces using Minitab software. The goal is therefore to find a mathematical model that minimizes drying time on the one hand and energy consumption on the other hand during drying. The experimental study conducted in a hybrid solar dryer designed at the Ecole Nationale Supérieure Polytechnique made it possible to obtain the experimental results that are processed using two software programs: Originpro8 and Minitab. The analysis of the main effect profiles as well as the mathematical correlation show the following:

- The energy consumption is proportional to air temperature, air velocity and wafer thickness.
- The drying time is proportional to the thickness of the slice and inversely proportional to the temperature (from the center of the domain to its upper level) and the air velocity.
- The good concordance with an overall desirability of 90.29% between the selected models and the experimental results was observed with correlation factors of 99.3% and 99.8% respectively for drying time and energy consumption and the optimal values of drying time DS=318.2922 minutes and energy consumption CE=7.1859 kwh are obtained by combining the following operating conditions:
- Drying air temperature of 40°C;
- A thickness of the product of 11.5mm ;
- An air velocity of 1.02m/s.

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