Optimisation of energy consumption of a solar-electric dryer during hot air drying of tomato slices

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Abstract

High-energy demand of convective crop dryers has prompted study on optimisation of dryer energy consumption for optimal and cost effective drying operation. This paper presents response surface optimisation of energy consumption of a solar-electric dryer during hot air drying of tomato slices. Drying experiments were conducted with 1 kg batch of tomato samples using a 3^3 central composite design of Design Expert 7.0 Statistical Package. Three levels of air velocity (1.0, 1.5 and 2.0 ms^{-1}), slice thickness (10, 15 and 20 mm) and air temperature (50, 60 and 70°C) were used to investigate their effects on energy consumption. A quadratic model was obtained with a high coefficient of determination (R^2) of 0.9825. The model was validated using the statistical analysis of the experimental parameters and normal probability plot of the energy consumption residuals. Results obtained indicate that the process parameters had significant quadratic effects (P<0.05) on the energy consumption. The energy consumption varied between 5.42 kWh and 99.78 kWh; whereas the specific energy consumption varied between 5.53 kWhkg^{-1} and 150.61 kWhkg^{-1}. The desirability index method was applied in predicting the ideal energy consumption and drying conditions for tomato slices in a solar-electric dryer. At optimum drying conditions of 1.94 ms^{-1} air velocity, 10.36 mm slice thickness and 68.4°C dry-ing air temperature, the corresponding energy consumption was 5.6 8kWh for maximum desirability index of 0.989. Thermal utilisation efficiency (TUE) of the sliced tomato samples ranged between 15 ≤TUE ≤58%. The maximum TUE value was obtained at 70°C air temperature, 1.0 ms^{-1} air velocity and 10 mm slice thickness treatment combination, whereas the minimum TUE was obtained at 50°C air temperature, 2.0 ms^{-1} air velocity and 20 mm slice thickness. Recommendation and prospect for further improvement of the dryer system were stated.

Introduction

Tomato (*Lycopersicon esculentum*) is a perishable and seasonal fruit vegetable grown and widely eaten in Nigeria and across the globe for its good health benefits such as reduction of cholesterol, improvement of vision, maintenance of gut, lowering of hypertension, alleviation of diabetes, protection of the skin, prevention of urinary tract infections and gallstones. It is characterised by being in good quality, rich in minerals, vitamins, organic acids, high moisture (usually above 85% wet basis), crude fibre, high lycopene, ascorbic acid and flavonoids (Abano *et al.,* 2014). In Nigeria, tomato yields about 20-50 tonnes ha^{-1} in every harvesting season. Eke (2013) reported that 20-60% of tomato produced in Nigeria rot away annually. These losses give rise to short supply and high prices during the off-season. This necessitates the need for efficient and adequate preservation techniques to increase its shelf life. Owing to its seasonal and perishable characteristics, drying becomes a good preservation alternative in order to increase its availability. Its drying is facilitated by slicing and spreading out the product to increase their surface area to hot convective air using a reliable heat source and increasing the airflow around the product. In recent times, dried tomatoes have become a highly attractive product for both domestic and industrial purposes which resulted in increased product demand. This is because the lycopene content, characteristic red colour, non-enzymatic browning and vitamin A (ascorbic acid) content are considered as the most vital quality criteria (Abano *et al.,* 2014).

Considerable amount of energy is consumed by convective dryers to dry most freshly harvested agricultural products to safe moisture level as a result of their relatively high moisture content (70 to 95% wet basis) at harvest which requires long drying time, low thermal conductivity during the falling rate drying period which inhibits convective heat transfer to the inner sections of the product structure, relatively low energy efficiency of dryers, and high latent heat of water evaporation (Motevali *et al.,* 2014; Nwakuba *et al.,* 2016). This high-energy consumption, however, has significant impact on the dried product quality such as its nutritional values, shrinkage and other organoleptic properties (Darvishi *et al.,* 2013). Dryer energy consumption is a vital technical information applied for optimal and cost effective design and

operation of drying systems as well as adequate meeting of safe storage conditions of crops (Nwakuba *et al.,* 2016). Energy consumption has been identified to vary with crop type, moisture content at harvest, final desired moisture content, specific heat capacity of crop, latent heat of vaporisation of water, intended use, gross mass, size, shape, and biological characteristics (such as surface texture, crop porosity, nutritional content), drying times, production capacity, drying air temperatures as well as operating pressure and dryer efficiency (Billiris *et al.,* 2011). Considerable energy savings in drying application can be achieved through partial or full replacement of conventional fuels by renewable energy sources. Extensive research regarding energy consumption of crop dryers has been prompted by the considerable energy consumption in the drying industry, as well as concerns for cost of drying agricultural products, its impact on the food supply chain, and environmental effects like increased prevalent ambient air temperature, increase in greenhouse gas, air pollution, *etc.* (Koyuncu *et al.,* 2007; Nwakuba *et al.,* 2016). Other reasons prompting the study of energy consumption include: estimating the quantity of fossil fuel saved when using solar energy and the quantity of CO_2 emitted into the atmosphere (Tripathy and Kumar, 2009); estimation of the optimum quantity of drying air temperature, air flow, and drying time most appropriate for a particular crop so as to avoid undermining the functional and sensory properties of the product; applicability in the design of appropriate cost and energy effective drying system which would require minimal quantity for any crop type; and for simulation of drying systems.

The use of solar energy as a practical power source for crop drying has been stimulated in recent times due to shortages of oil and natural gas fuels and increase in the cost and depletion of fossil fuels (Nwajinka and Onuegbu, 2014). This power source has been harnessed for heating, cooling, drying, irrigation, pumping, and other numerous thermal processes in food industries (Itodo *et al.,* 2002). Over 90% of agricultural products are sun-dried in Nigeria and in most African countries (Arinze *et al.,* 1990). Unfortunately, much of this commonly available, renewable and affordable energy from the sun is wasted due to lack of adequate technology to harness it. The daily and seasonal fluctuations in solar radiation as well as its frequent absorption by rain and persistent cloud cover in most parts of the country and the world at large have hampered the optimal use of the Sun's energy for crop drying operation and therefore necessitate the additional use of energy source that permits drying operation during low irradiation and night periods. Researchers Ferreira *et al.* (2007), Sarsavadia (2007) and Nwakuba *et al.* (2017) have incorporated electricity as a viable auxiliary source of energy in solar drying systems due to its non-polluting characteristics, ease of usage and high heat density. The increased emphasis on rural development in Nigeria which undoubtedly will necessitate increase in energy demand in the rural sector for drying and other agricultural processes, makes the use of solar-electric dryers cost effective and environmentally friendly. Reducing the energy consumption in these systems irrespective of the crop to be dried would grossly improve the dryer economy. Since the sliced tomato price and quality are functions of energy consumption during drying, it is essential to select optimal drying variables that would yield minimal energy and carbon footprint on the natural environment while keeping the nutritional quality of the sliced tomato unabated and intact with minimal deterioration. The objective of this study is to investigate the effects of the drying variables (air velocity, sample thickness, and drying air temperature) on the total and specific energy consumption of a solar-electric dryer and to optimise the energy consumption of tomato slices during hot air drying.

Materials and methods

Sample preparation

A local variety of fresh tomato samples (*Gboko Spp.*) were procured from a fruit market in Owerri, Imo State, Nigeria. The samples were selected based on uniform colour, and carefully sorted to remove damaged or septic ones, and classified according to relative size, washed and sliced in three layer thicknesses (10, 15 and 20 mm) using a sharp stainless steel knife and a vernier caliper (accuracy 0.05 mm) with the direction of cutting perpendicular to the vertical axis of the tomato samples. The initial mass of the sliced samples was measured by a digital weighing balance (of accuracy 0.01 g; Camry instruments, China) and the samples placed on drying racks in such a way that the drying air flows axially into the sample matrix (for faster drying) in thin layers. The mean initial moisture content of 19.57 kg water/dry weight of the samples was determined gravimetrically measured by drying 20g of representative sliced samples at 105°C for 24 h (Koyuncu *et al.,* 2007; Darvishi *et al.,* 2013).

Drying system and experimental procedure

The solar-electric dryer (Figure 1) was switched on and the required airflow and temperature were selected using a 4×4 matrix keypad panel on the control unit. The nucleus of the crop dryer is the arduino microprocessor which controls the overall operation of the system and automates temperature and humidity control, air flow, sample weight loss, and energy consumption through the use of weight sensors and transducers (thermistor and humidity sensors) placed on five locations of the drying system *viz*: drying racks, solar collector box, inlet and outlet points. The drying chamber was allowed to maintain a steady-state condition (*i.e.* a state of uniform air temperature and relative humidity maintained in the drying chamber) before the sliced samples were introduced. The dryer was operated at three varying air temperature thresholds (50, 60 and 70°C), air velocities (1.0, 1.5 and 2.0 ms⁻¹) and slice thicknesses (10, 15 and 20 mm). Sliced tomato samples (1000 g) were placed on the drying racks, side-by-side in thin layers, in such a way that each sliced sample/layer was placed axially to the direction of heat flow for uniform drying. The system was programmed via the arduino micro-processor, to measure and record the energy consumption and weight loss in 30 min interval as well as the air temperature and relative humidity of the five points on the dryer. The amount of moisture loss was recorded using a weight sensor attached to the weighing balance in the drying chamber (Figure 1, S/N 18). Drying of each batch was stopped when constant mass was observed. The amount of electrical energy consumed, drying rate and time for each sample batch (at varying air velocities, slice thicknesses, and temperatures) were measured and recorded by the micro-processor, whereas the amount of solar flux incident on the solar collector was measured by a pyranometer (Apogee MP-200), the specific energy consumption calculated and thermal utilisation of efficiency of the system were calculated. The experiment was repeated three times for different air velocities, sample layer thicknesses and drying air temperatures for a constant batch size of 1 kg.

Experimental design and data analysis

The response surface methodology (RSM) of Design Expert version 7.0 (Stat ease Inc., Minneapolis, MN, USA) statistical package was used to design and analyse the drying experiments as well as determining the relative contributions of the three independent variables (air velocity, A: 1.0, 1.5 and 2.0 ms⁻¹; sample slice

thickness, S: 10, 15 and 20 mm; and drying air temperature, T: 50, 60 and 70°C) to energy consumption (E_C) responses. A three-factor and three-level (3^3) central composite design (CCD) of RSM arrangements was applied to evaluate the linear (main), interactive and quadratic (curvature) effects of the process parameters, to optimise the energy consumption of a convective solar-electric during the drying process of tomato slices. The central composite design used has 20 experimental runs and the experimental order had been completely randomised to reduce unexplainable variability effects from the experimental responses. Multiple regression approach was employed using the method of least squares in the data analyses. The response of the experimental values was expressed as Equation (1) by a second order polynomial function:

$$V_R = \beta_0 + \beta_1 A + \beta_2 S + \beta_3 T + \beta_{11} A^2 + \beta_{22} S^2 + \beta_{33} T^2 + \beta_{12} AS + \beta_{13} AT + \beta_{23} ST$$

(1)

where: V_R = response variable (E_{sp}, kWh); A, S and T represent air velocity (ms^{-1}), slice thickness (mm) and temperature (°C) respectively; β_0= constant regression coefficient; β_1, β_2 and β_3 linear regression coefficients; β_{11}, β_{22} and β_{33} = quadratic regression coefficients; β_{12}, β_{13} and β_{23}= interaction or cross-product regression coefficients.

The actual and coded values of the variables are presented in Table 1. The test for level of statistical significance was conducted on the total error criteria, having 95% level of confidence. Analysis of variance (ANOVA) was used to determine the significant variables in the model for the response of energy consumption. The model adequacies were checked by calculating R^2, adjusted R^2, adequate precision, PRESS and CV, whereas response surface optimisation was conducted using numerical optimisation technique. Desired goals (minimisation of energy consumption) was adopted to perform optimisation of process variables and the response. A multivariate response method, also referred to as overall desirability function or index, DI (Kumar *et al.,* 2011; Abano *et al.,* 2014) expressed as Equation (2) was also used:

$$D_i = (Y_1 \times Y_2 \times ..., Y_n)^{\frac{1}{n}}$$

(2)

where: Y_i (i = 1, 2, 3, …, n) = responses; n = total number of responses; $0 \le D_i \le 1$, with 0 and 1 being the least and most desirable coded levels respectively. D_i = desirability index or composite function illustrating how well matched or desirable the experimental responses are at a given level of independent/input variables. The RSM optimisation process involves goals and priorities for input and response variables (Abano *et al.,* 2014). This study considers goal for the input variables at any level within the design value range, whereas the response variable was minimum energy consumption.

Table 1. Factor levels of the actual and coded variables of the response surface methodology factorial design.

Process variable	Symbol	Levels	
		Actual	Coded
Air velocity (ms^{-1})	A	1.0	−1
		1.5	0
		2.0	1
Slice thickness (mm)	S	10	−1
		15	0
		20	1
Temperature (°C)	T	50	−1
		60	0
		70	1
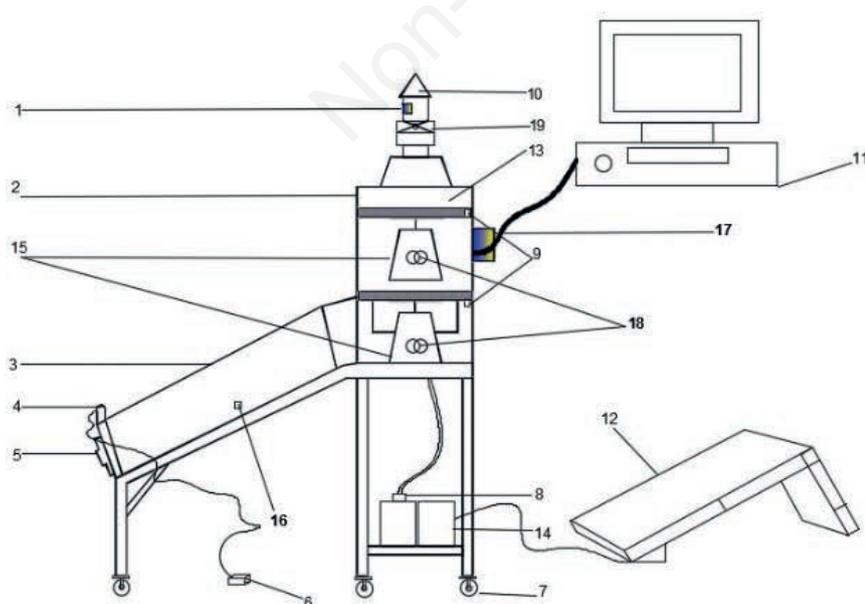
ITEM	DESCRIPTION
1	Temperature/ humidity sensor
2	Drying chamber
3	Solar collector
4	Pyranometer sensor
5	Inlet fan
6	Pyranometer
7	Roller
8	Battery
9	Chamber temp/ humidity sensor
10	Chimney
11	Personal computer
12	Solar panel
13	Control unit
14	Solar charge controller
15	Weighing balance
16	Solar collector temp/humidity sensor
17	Control unit
18	Weight sensors
19	Exhaust fan

Figure 1. Schematics of the solar-electric drying system.

Energy consumption of sliced tomato drying

The total energy consumed by 1kg batch of the sliced tomato samples in the solar-electric crop dryer at varying air velocities, slice thicknesses, and air temperatures is expressed in Equation (3) (Afolabi *et al.*, 2014; Koyuncu *et al.*, 2007) as:

$$E_T = AV\rho_a C_{pa}\Delta T D_t \tag{3}$$

where: A = area of rack (m^2), V = air velocity (ms^{-1}), ρ_a = air density (kgm^{-3}), D_t = total drying time per batch (h), ΔT = temperature difference between ambient and hot air (°C), and C_{pa} = specific heat of air (kJkg^{-1}°C);

The specific energy consumption is expressed by Equation (4) (Koyuncu *et al.*, 2007; Afolabi *et al.*, 2014; Minaei *et al.*, 2014) as:

$$E_{SP} = \frac{E_T}{M_0} \tag{4}$$

where: E_T = total energy consumption per batch (kWh); E_{sp} = specific energy consumption (kWhkg^{-1}); M_0 = initial sample mass (kg).

The total energy consumption (E_T) of the dryer in drying a batch (1 kg) of sliced tomato samples at varying drying conditions was obtained by adding the energy directly measured by the arduino micro-processor in 30 minutes intervals to the solar energy absorbed by the solar collector (measured by the pyranometer). The measured E_T was compared with the calculated (from Equation 1), which was less by an average of 8.14% of the calculated E_T values. This marginal difference was as a result of the constant air density and air velocity used in the calculated E_T values; whereas in the measured E_C values, varying air velocities were considered by the arduino-primed dryer system where air densities vary with air temperature, thus a negligible value difference. The calculated E_T values were used to calibrate the arduino micro-controller as well as validating the system-measured E_T values.

Thermal utilisation efficiency

The thermal utilisation efficiency (TUE) shows how well a drying system converts thermal energy or accomplishes heat transfer process during drying operation. It is referred to as the ratio of latent heat of evaporation of sample internal water to the energy consumption for moisture evaporation from free water. TUE was determined using Equation (5) (Minaei *et al.*, 2014; Beigi, 2016):

$$\eta_{th} = \frac{WA_s L_v (M_i - M_f)}{Qt(100 - M_f)} \tag{5}$$

where: η_{th} = thermal utilisation efficiecy (%); W = weight density of sample (kgm^{-2}); A_s = total sample area (m^2); L_v = latent heat of vaporisation (kJkg^{-1}); M_i and M_f = initial and final moisture contents respectively (%w.b); Q = power of the heat source (kW); t = operation time of the heat source (minutes).

The latent heat of evaporation of the sliced samples was considered equal to the latent heat at ambient air pressure (Minaei *et al.*, 2014).

Results and discussion

Effect of drying parameters on energy consumption

The energy consumption responses of the twenty experimental runs performed at varying process variables with CCD are presented in Table 2. The experimental data were used to determine the coefficients of the independent/input variables, as well as the interactions between them (Table 3). Experimental results of the second order quadratic model fitted to the response variable (energy consumption) in terms of the coded variables is given in Equation (6) as:

$$E_c = 22.07 - 8.58A + 23.43S - 23.98T + 20.01A^2 + 5.77S^2 + 21.81T^2 - 4.27AS - 9.39AT - 7.13ST \qquad [R^2 = 0.9825] \tag{6}$$

where: A, S and T are the coded values of air velocity (ms^{-1}), sample slice thickness (mm), and temperature (°C) respectively; E_c = energy consumption (kWh).

Analysis of variance (ANOVA) of Equation (1) (Table 3) indicates that P-values for linear terms had significant effect on energy consumption (P<0.05). Equation (6) shows that variables A and T had negative coefficients, whereas S was positive. This implies that increase in air velocity and temperature may reduce the energy consumption significantly and further increase in the sample slice thickness may increase the energy consumption quantitatively.

Table 2. Central composite design for three experimental factors of the process variables and responses (energy consumption and lycopene content).

Run No.	Actual process variables			Response variables
	A (ms^{-1})	S (mm)	T (°C)	EC (kWh)
1	1.05	6.93	60.00	30.9
2	2.00	19.00	70.00	43.5
3	1.05	14.50	76.82	93.0
4	1.05	14.50	60.00	80.0
5	1.05	22.07	60.00	83.9
6	1.05	14.50	60.00	80.0
7	−0.55	14.50	60.00	85.1
8	1.05	14.50	60.00	80.0
9	1.05	14.50	60.00	80.0
10	2.00	19.00	50.00	70.6
11	0.10	10.00	50.00	32.0
12	1.05	14.50	43.18	86.5
13	1.05	14.50	60.00	80.0
14	1.05	14.50	60.00	80.0
15	2.00	10.00	70.00	22.5
16	0.10	10.00	70.00	42.0
17	0.10	19.00	70.00	70.0
18	2.65	14.50	60.00	31.9
19	2.00	10.00	50.00	42.4
20	0.10	19.00	50.00	102.0

From the ANOVA, the quadratic energy model is highly significant at P<0.05, with a high coefficient of determination (R^2) of 0.9825. This illustrated that a greater percentage of the experimental variability was described by the RSM model (Abano *et al.*, 2014). A coefficient of variability (CV) less than 10% was observed (Giri and Prasad, 2007; Kumar *et al.*, 2011), and it indicates that the quadratic model adequately represented the experimental data and closely predicted the energy consumption of the solar-electric dryer for drying of tomato slices as observed by Kumar *et al.* (2011). The suitability of the second-order quadratic model was further validated with the normal probability plot of the energy consumption residuals as shown in Figure 2A, and the predicted and experimental energy consumption plot (Figure 2B). The close-

ness of the plotted data (of both plots) to the straight line showed equality between the predicted and experimental energy consumption values as well as indicating that no problem existed between the normality and severity of outliers in the experimental data of energy consumption. The positive coefficients of the quadratic terms of AST factors show positive quadratic effect on energy consumption of the dryer. The interaction or cross-product effect of the process variables on energy consumption of solar-electric dried tomato sliced samples is presented in response surface plots (Figure 3A and C). The cross-product interaction effect between air velocity and slice thickness, air velocity and air temperature, as well as the quadratic effect of air velocity were insignificant (P≥0.05) to energy consumption, whereas other terms were signif-
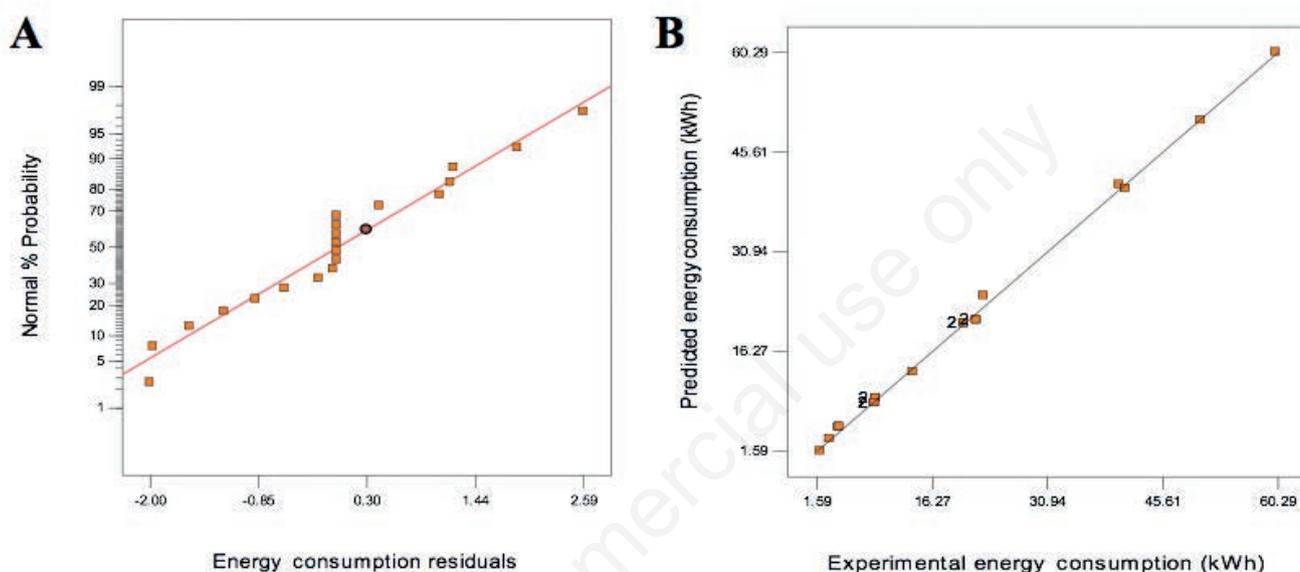
Figure 2. A) Normal probability plot of the energy consumption residuals; B) predicted *versus* experimental energy consumption.

Table 3. Analysis of variance for energy consumption at varying drying conditions by response surface quadratic model.

Source	Degrees of freedom	Coefficient estimate	Sum of squares	Mean square	F-value	P-value Prob > F
Intercept (β_0)	9	22.07				
Model	1		14,383.43	1598.16	7.81	<0.0001*
A - Air velocity	1	−8.58	589.45	589.45	12.60	0.0392*
S - Slice thickness	1	23.43	4393.59	4393.59	28.73	<0.0011*
T - Temperature	1	−23.98	4600.80	4600.80	1.74	<0.0001*
A^2	1	20.01	1686.32	1686.32	11.62	0.5247 ns
S^2	1	5.77	140.42	140.42	12.48	0.0002*
T^2	1	21.81	2002.39	2002.39	14.12	<0.0001*
A×S	1	−4.27	73.02	73.02	2.09	0.0714 ns
A×T	1	−9.39	352.69	352.69	1.55	0.3301ns
S×T	1	−7.13	203.21	203.21	2.12	0.0032*
Residual	7	-	21.12	-	-	-
Lack of fit	3	-	5.47	-	-	-
Pure error	4	-	0.00	-	-	-
Cor. Total	16	-	14,390.54	-	-	-
CV			3.91			

*Significant; ns not significant; lack of fit is not significant at P>0.05.

icant (P<0.05). As illustrated in Table 3 and Figure 3A-C, energy consumption of the solar-electric dryer had a significant decrease as air velocity and air temperature were increased. Air temperature had the highest effect on energy consumption (<0.0001), followed by the slice thickness (<0.0011) then the air velocity (<0.0392). The minimum total energy consumption (5.42 kWh) was obtained at the highest drying air temperature, air velocity and least slice thickness, whereas the maximum energy consumption (99.78 kWh) was obtained at the least air velocity, air temperature and thickness slice sample (Figure 3A and C). At increased air temperature and air velocity, mean energy consumption reduced; greater heat transfer rate and water pressure deficit occurred, more convective air entered the drying chamber to increase surface moisture

evaporation rate as well as increasing the sample kinetic energy of internal moisture for rapid diffusion and reduced resistance to capillary transport. This gave rise to increased heat and moisture diffusion and evaporation is accomplished in a shorter time, thereby reducing the amount of energy consumption which is a function of drying time. Similar trend was observed in the works of Abano *et al.* (2014), Minaei *et al.* (2014), and Sepehrimehr and Kohan (2015).

At reduced air velocity, more energy was consumed when drying thicker sliced tomato samples (Figure 3B). This was as a result of gross reduction in mass transfer rate and increased capillary distance for moisture diffusion. With increased drying air temperature and decreased sample slice thickness, less energy was consumed
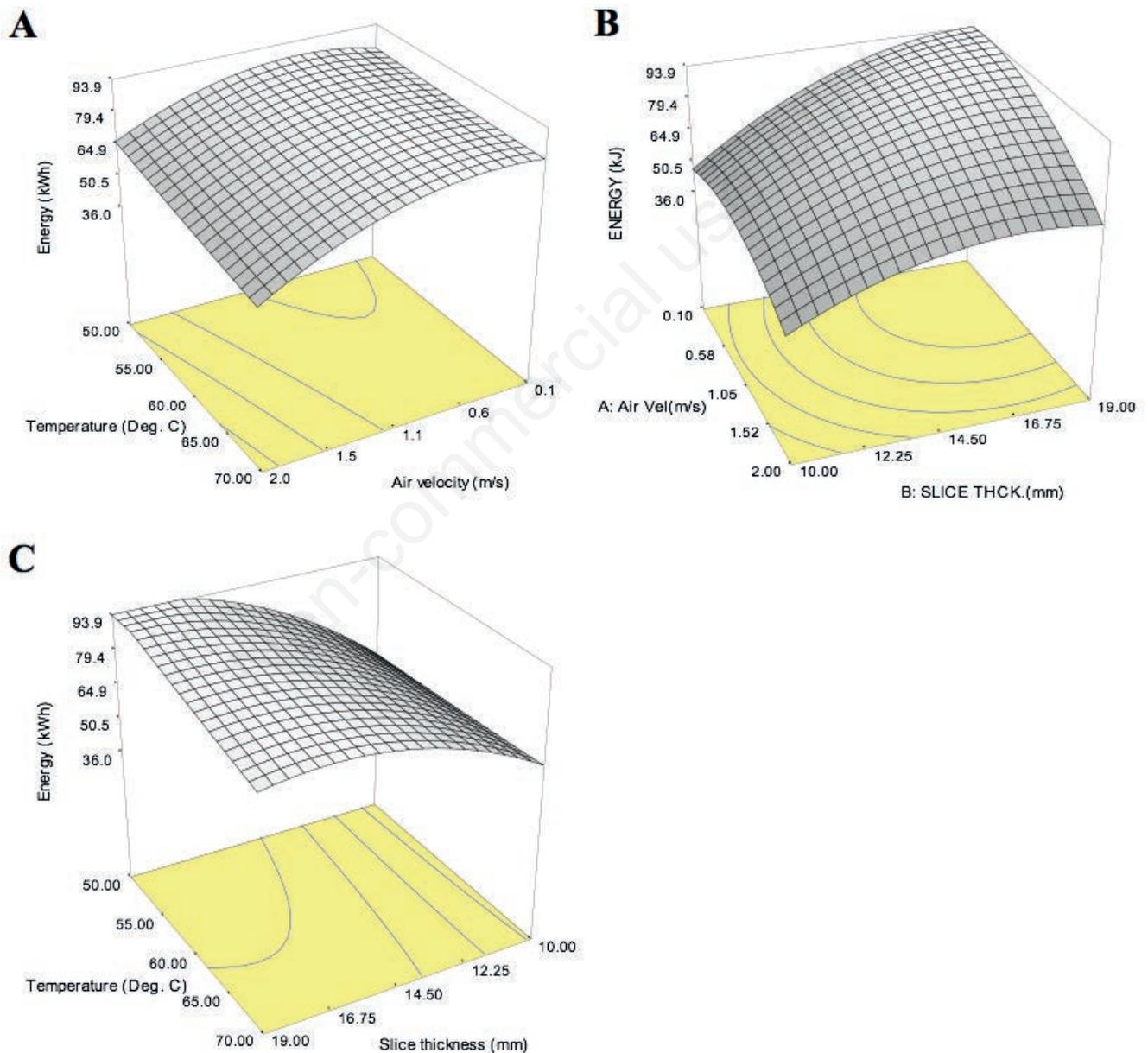
Figure 3. Response surface plot showing: A) the effect of air velocity and temperature; B) air velocity and slice thickness; C) slice thickness and temperature on energy consumption.

(Figure 3C), since more moisture diffused at increased air temperature and drying time decreased, thus the reduction in energy consumption.

Specific energy consumption

The specific energy consumption for drying a batch of the sliced tomato samples at varying process parameters is presented in Figure 4. Specific energy consumption decreased with decrease in slice thickness at any given air temperature and air velocity. The maximum specific energy consumption (150.6 kWhkg^{-1}) was obtained at the 20 mm slice thickness. It also decreased with increase in air temperature at constant air velocity and slice thickness. This is because with increasing material thickness, the total energy consumption increases as it is divided by a constant initial sample weight. Specific energy consumption was thus calculated by substituting the measured value of the total consumed energy obtained from the arduino micro-processor as well as the initial sample weight into Equation (4).

It is evident that air velocity, air temperature and slice thickness had remarkable effects on the specific energy consumption of the solar-electric dryer. Increase in drying air temperature reduced the specific energy consumption since more moisture was removed in a shorter time per sample batch size. Drying a larger sample thickness at a low air temperature and air velocity increased the specific energy consumption. This is because, more time was taken for the larger sample layer to diffuse internal moisture to the product surface before the slow-moving convective air evaporates the surface moisture, thus increased drying time and energy. The maximum and minimum specific energy consumption (150.61 kWhkg^{-1} and 5.53 kWhkg^{-1} respectively) were obtained at the first and last drying parameter regimes: 50°C, 20 mm, 1.0 ms^{-1} and 70°C, 10 mm, 2 ms^{-1} respectively. This generally implied that less energy was con-

sumed at increased air temperature and air velocity for drying any sample thickness. This corroborated with the findings of Sharma and Prasad (2006) for glarlic cloves, Jindarat *et al.* (2011) for non-hygroscopic materials, Afolabi *et al.* (2014) for ginger slices, El-Mesery and Mwithiga (2012) for onions slices with a decreasing trend in specific energy consumption with increase in the drying air temperature and air velocity.

Optimisation of energy consumption

The concept of overall desirability function (Equation 2) of Design Expert 7.0 version was used to affirm the position of the optimal energy consumption of the solar-electric dryer. The desired objective (goal) for each input parameter and responses were allotted to each parameter to make adjustment for its desirability index (Table 4). The optimum values of the process parameters yielded an overall desirability function of 0.989 at 98% confidence level in the range of the process parameters, which yielded an optimal energy consumption of 5.68 kWh for 1.94 ms^{-1}, 68.4°C, and 10.36 mm air velocity, air temperature and slice thickness respectively. The optimisation process of the solar-electric dryer gets better as the desirability function is close to unity. Interestingly, these predicted values though had little deviation from their corresponding experimental input variables but were still within the range (Table 4). Therefore, the quadratic model obtained from this study (Equation 6) could be applied in the optimisation of energy consumption of solar-electric dryers during drying of sliced tomato samples.

Thermal utilisation efficiency

The thermal utilisation efficiency (TUE) of the solar dryer at varying air velocities, slice thicknesses and air temperatures was calculated using Equation (5), and the results were presented in Figure 5. TUE increased with increasing drying air temperature at
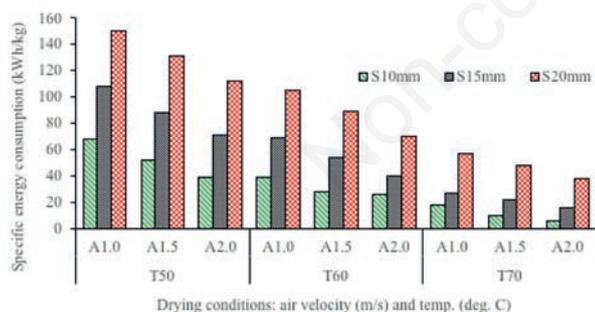
Figure 4. Specific energy consumption of the solar-electric dryer for drying a batch of tomato slices.
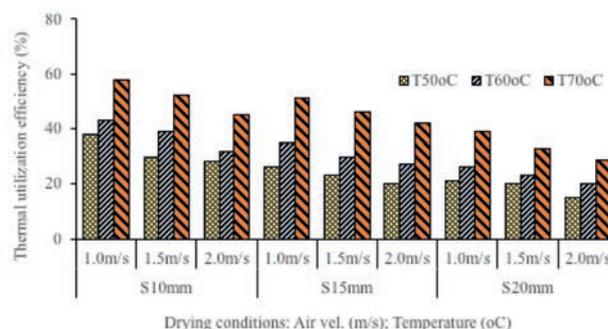
Figure 5. Thermal utilisation efficiency of the solar-electric dryer at varying drying conditions.

Table 4. Objective function and criteria for optimisation of process factors and response.

Responses	Goal	Lower limit		Upper limit		Importance
		Actual	Coded	Actual	Coded	
Air velocity (ms^{-1})	In range	1 ms^{-1}	−1	2 ms^{-1}	1	3
Temperature (°C)	In range	50°C	−1	70°C	1	3
Slice thickness (mm)	In range	10 mm	−1	20 mm	1	3
Energy consumption (kWh)	Minimise	-		-	-	3

constant air velocity and slice thickness, and decreased with increase in air velocity and slice thickness. This was because higher drying air temperatures result in further reduction of moisture, which increased energy utilisation efficiency. These observations are in line with Aviara *et al.* (2014) on tray drying of cassava starch; Azadbakht *et al.* (2017) on eggplant drying in a fluidised bed dryer. The maximum TUE value was obtained at 70°C air temperature, 1.0 ms^{-1} air velocity and 10 mm slice thickness, whereas the minimum TUE was obtained at 50°C air temperature, 2.0 ms^{-1} air velocity and 20 mm slice thickness. These results agreed with those reported in the literature (Sarsavadia, 2007; El-Mesery and Mwithiga, 2012; Minaei *et al.,* 2014; Motevali *et al.,* 2014).

Since TUE is the ratio of energy used for water evaporation to energy consumed (supplied), with increased slice thickness, part of the utilised heat was used to increase the product temperature so as to overcome the energy barrier (activation energy level) as a result of longer capillary distance and initiate mass diffusion, thereby leaving a little amount of heat for surface moisture evaporation, thus low thermal efficiency. However, with decreasing slice thickness, TUE increased due to increase in the interface between the product and the drying air (Azadbakht *et al.,* 2017). Drying air at low velocity tends to have more resident time of contact with the drying sample and evaporates the surface moisture more efficiently than when it is at a higher velocity, which may create turbulence at the inlet and plenum of the drying chamber and exits without having much contact effect on the samples. From Figure 5, it is evident that TUE of the convective solar dryer is a function of the heat source performance and initial weight of the product sample, since the initial and final moisture contents as well as the latent heat of vaporisation of water were considered constant (Minaei *et al.,* 2014). High TUE of the system is related to good performance of the heating units, which are controlled by the microprocessor to regulate the drying air temperature within a preset threshold at regulated air velocities.

Conclusions

Optimisation of energy consumption of a solar-electric dryer was studied using sliced fresh tomato samples at varying process parameters (air velocity, A: 1.0, 1.5 and 2.0 ms^{-1}; slice thickness, S: 10, 15 and 20 mm; air temperature, A: 50, 60 and 70°C) using a 3^3 central composite design of Design Expert 7.0 statistical package to investigate the effects of the process parameters on the response variable (energy consumption). The AST factors had significant quadratic effects (P<0.05) on the energy consumption of the solar-electric dryer. The quadratic energy model was highly significant at P<0.05, with a coefficient of determination (R^2) of 0.9825, which had CV less than 10% indicating adequate representation of the experimental data and accurate prediction of energy consumption.

Drying air temperature had the highest effect on energy consumption, followed by slice thickness and air velocity, respectively. Energy consumption had a significant decrease as air velocity and air temperature were increased. The minimum energy consumption (5.42 kWh) was obtained at the highest drying air temperature, air velocity and least slice thickness (70°C, 1 ms^{-1}, and 10 mm), whereas the maximum energy consumption (99.78 kWh) was obtained at the least air velocity, air temperature and slice thickness (50°C, 1 ms^{-1}, and 10 mm). The maximum and minimum specific energy consumption (150.61 kWhkg^{-1} and 5.53 kWhkg^{-1}, respectively) were obtained at the first and last drying

parameter regimes: 50°C, 20 mm, 1.0 ms^{-1} and 70°C, 10 mm, 2 ms^{-1}, respectively.

Three-dimensional response surface plots of the interaction effects of the process variables on the response variable were developed. The prediction of the desirability function based on 98% level of confidence in the range of the input variables yielded an optimal process parameters of 1.94 ms^{-1}, 10.36 mm and 68.4°C for air velocity, slice thickness and air temperature, respectively. At this optimum input condition, the corresponding energy consumption was obtained as 5.68 kWh.

The TUE of the dryer at varying process parameters was in the range of 15-58%. The maximum TUE (58%) value was obtained at 70°C air temperature, 1.0 ms^{-1} air velocity and 10 mm slice thickness treatment combination, whereas the minimum TUE (15%) was obtained at 50°C air temperature, 2.0 ms^{-1} air velocity and 20 mm slice thickness.

It is recommended that ±0.1 of the optimal drying conditions should be maintained for economy. Further studies on performance analysis and optimisation of energy consumption of solar-electric dryers with heat recovery units for different sliced fruit vegetables are of considerable interest.

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