Influence of process parameters on the energy requirements and dried sliced tomato quality

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Abstract
This study presents the effects of process parameters on the energy demand for drying and quality indices of dried tomato slices. The experiment was designed and analyzed with the Box-Behnken method of Design Expert and conducted for drying 1800 g batch of a local variety of tomatoes with a solar-electric dryer. The study examined the impact of varying process parameters: air temperature (50°C, 60°C, and 70°C), sample thicknesses (10, 15, and 20 mm), and air velocities (1.0, 1.5, and 2.0 ms⁻¹) on the total and specific energy requirements, drying time, lycopene content, ascorbic acid, nonenzymatic browning index, brightness, and ratio of redness to yellowness of dried tomato samples, with emphasis on process optimization and drying time. The prediction of the optimal process condition is obtained using the desirability index technique. The results obtained show that the total and specific energy requirements for a batch of tomato varied from 7.82 to 125.48 kJ h and 6.70 to 179.83 kJ h g⁻¹. The results of the analysis of variance (ANOVA) indicate that all the studied process parameters were significant with P > .05; with the maximum (40.21%) and minimum (19.82%) percent energy contribution by air temperature and air velocity, respectively. The energy of activation varies between 20.26 and 39.35 kJ mol⁻¹. At the optimum process conditions of 57.28°C, 14.08 mm, and 1.3 ms⁻¹, the specific energy requirements, lycopene content, ascorbic acid content, nonenzymatic browning index, brightness, redness to yellowness ratio, and drying duration are obtained as 103.313 ± 2.35 kWh kg⁻¹, 58.7 ± 2.19 mg/100 mg dry matter, 2.9 ± 0.26 mg/g, 0.51 ± 0.033 absorbance unit, 60.074 ± 1.44, 0.77 ± 0.021, and 61.88 ± 8.93 minutes, respectively. The results of the study are of immense benefit to the food drying industry, as it provides food industries with improved drying parameters for enhancing dried tomato quality, as well as increasing dryer energy efficiency and cost-effectiveness. Suggestions on prospects for further studies were given.

KEYWORDS
convective drying, energy requirements, process parameters, quality indices
1 | INTRODUCTION

Tomato (Lycopersicon esculentum L.) is a vegetable generally known for its perishable nature; seasonal in production, grown and consumed in most countries. Tomatoes are the second most important vegetable crop after potato in economic terms. Tomato is a seasonal crop, whose fruit contains high mineral and vitamin contents, with moisture content above 90% w.b., as well as little fats deposit particularly when freshly harvested, and deteriorate fast when not well preserved in fresh form. In Nigeria, it is produced in large quantities between the months of October and March, and consumed fresh or sold at very cheap prices in order to avoid rotting away. It is commercially produced in the northern region of Nigeria and marketed to the southern region and neighboring countries. Huge postharvest losses of tomato during its peak period has been a great challenge facing many developing nations like Nigeria, as a result of inadequate postharvest technology and predominantly open-sun drying technique used for its processing. Nwakuba (2019) reported that about 20% to 60% of tomatoes produced in Nigeria and other tropical countries go into waste annually due to poor postharvest processing which results in product scarcity and higher prices.

In recent years, consumer demand for tomato products has increased. Its rapid growth in both domestic and international markets has much it being used for convenience food preparation. To preserve tomato in dried form for market availability out of season, it undergoes dehydration process, which is characterized with high energy demand, because of decreased energy efficiency of convective crop dryers (with regards to other forms of artificial dryers), low thermal conductivity during the falling rate drying period. This impedes heat transfer by convection to food matrix with high latent heat capacity of evaporated water. Drying has noticeable effects on the dried product quality indices such as its nutritional value, color, flavor, shrinkage, and other organoleptic properties and should be applied in such a way as to cause minimal changes in dried product quality as well as uses less energy. In Nigeria, sun drying is the most widely used technique for drying of tomato and other agricultural products, among other drying techniques of tomato. This is as a result of the strategic location of Nigeria within the world’s high sunshine belt, which positions it advantageously to harness large quantity of solar radiation per square meter, and its low level of technological development. Recently in Nigeria and most other developing economies, the use of solar energy for drying of crops has been enthused due to as a result of deficiencies in oil and natural gas and prevailing price hike as well as apprehension of fossil fuel depletion. The predominantly used open-air sun-drying technique by direct exposure of product to solar radiation and prevailing wind is a cheap and old practice which results in poor quality of products due to its weather dependency, slow drying process, pollution and considerable loss due to rodents, birds, insects and micro-organisms; no protection from unexpected rain, insufficient drying, over drying, discoloring by ultraviolet (UV) radiations, nutritional deterioration, loss of flavour, taste, case-hardening. Studies on thermal performance of open-sun drying system for different crops indicate that convective heat-transfer coefficient vary significantly with type and initial moisture content of crops. In order to make greater increase in the use of the available process conditions as well as source of energy applied, different dehydration processes have been established. Drying, as a classical food dehydration technique has been distinguished for maintaining crops’ desired quality for lengthy period.

On the other hand, the erratic nature of solar irradiation, especially in the South-eastern Nigeria nearer to the Atlantic Ocean and regional catchment water bodies, as well as incessant enfeeblement of sunshine period by high rainfall intensity, have grossly narrowed the productive application of solar energy for crop drying purposes. To overcome these limitations, closed sun-drying systems (artificial dryers) primed with microprocessors were developed as a more scientific method to utilize the Sun’s energy, automatically adjust dryer’s working conditions (with little or no human supervision) in order effect the necessary air enthalpy for optimal drying and eventual preservation of the product quality, increase its shelf life, improve product diversity, reduce cost of packing, storing, transportation, and process applications. These improvements led to increase in the current acceptance of dehydrated food products in both domestic and international markets and increased the gross domestic product (GDP) of the developing economies, hence justify the need for drying sliced tomato in convective crop dryers.

As a result of Nigeria’s present energy deficit, more reliable drying techniques have been developed by modern technology advances for crop drying applications. Researches are propagating hybrid drying systems integrated with other heat units (like biomass heater, electric resistance wire, gas, etc) to make up for the deficient solar heat generation during low irradiation periods. This provides for sustained drying operation during night periods and low sunshine hours; precludes moisture reabsorption, especially for moisture-laden crops like tomato, which results in gross decrease in total drying time and energy consumption, as well as enhanced drying rate. Some researchers had reported the integration and application of electric heat to solar dryer as a worthwhile supplementary source of energy.
of its simplicity of application, clean nature, and high net heat density, electricity makes provision for gross reduction in drying energy cost, as well as minimization of atmospheric carbon emission by other conventional sources of energy, when used for drying. Unfortunately, most rural dwellers in Nigeria are currently challenged with irregular or zero supply of electric power, which has resulted in sharp increase in the price of dried agricultural food products. However, the intensified effort of the Nigerian Government on rural development has brought hope for increased level of energy need in both the rural and urban areas for crop drying and other farm production applications. This considers the use of solar electric-assisted crop dryers economical and safe. As a result of the energy intensive nature of crop drying process, any approach toward reduction of energy costs to improve efficiency of crop dryers for high quality dried food products is supported by food processors.23-25

However, energy requirements have direct effect on the dried product, and so equilibrium should be maintained between product quality and minimizing energy requirements for drying cost reduction. Quality of dried food products is generally assessed by its nutritional value, acceptability and safety. The degree of acceptability of dried products majorly depends on color and taste attributes26 and drying as well as air condition (drying air temperature, air velocity, and air relative humidity) and moisture content. For sliced vegetables, the optimal selection of drying conditions depends on the total drying duration whereas the price of the dried product depends on its final quality.27 These optimal conditions also help in preserving the product nutrient, minimize energy requirements for drying, operation cost with marginal upturn in economic input and gross reduction in greenhouse gas (GHG) emissions.26,28,29

Some studies on energy requirements for drying of sliced agricultural products such as, pepper slices30; onion slices31; sliced banana, mango, potato, apple32,33; ginger slices34 revealed that by increasing air temperature at constant sample thickness and air velocity, the energy requirements, drying duration, and dryer energy consumption decrease, thus increase in drying rate. Similarly, experimental studies have been done on drying conditions for quality sliced dried products using different drying systems.26,29,35-37 In Nigeria, the interest in studies that investigate process conditions and energy requirements for good dried quality of tomato is recent. This formed the motivational basis for this research work. However, this study is based on the scientific publications of Abano et al,1 Reyes et al,5 and Correia et al,6 in which only the effects of air temperature, drying time and sample thickness on the sensory qualities of unsliced/whole dried tomato samples were considered, whereas this work investigates the interaction of the process parameters with sensory qualities of sliced tomato samples, vis-à-vis the energy requirement for optimal drying process. This study focuses on the influence of process conditions on the energy requirements and quality characteristics of dried tomato slices in a hot air convective hybrid solar dryer. The yield was investigated by applying a 3³ factorial treatment design using the Box-Behnken Design experimental tool.

Given the need to achieve considerable energy savings during drying process of moisture-laden tomato fruit and concerns for its drying cost, its impact on the food supply chain, environmental influences, as well as estimation of the best quantity of drying air temperature, air velocity and drying duration most suitable for a tomato crop in order not to undermine its nutritional qualities, justifies this study. This article hopes to develop suitable predictive mathematical models for energy requirements and drying parameters, as well as drying duration and drying parameters. It further illustrated the influence of the drying parameters on energy of activation, moisture diffusion kinetics during convective drying process and optimal drying conditions for good quality dried tomato slices.

2 MATERIALS AND METHODS

2.1 Sample preparation

A fresh local tomato sample variety (Gboko) was obtained from a municipal vegetable market in Owerri, south-eastern Nigeria. Viable samples (1.8 kg) with uniform color were selected and sorted based on size; washed with clean water, and sliced to three different layer thicknesses (10, 15 and 20 mm) using a stainless steel knife and a digital vernier calliper (accuracy ±0.05 mm) with the cutting at right angle to the samples vertical axis. A digital-type mass balance (precision ±0.01 g; Camry Instruments Ltd., China) was used for measuring the initial mass of the sliced tomato samples. The sliced samples were placed in side-by-side arrangement on the drying trays (Figure 1) so as to permit axial flow of convective drying hot air into the sample matrix. A representative sample of 20 g was dried at 105°C for 24 hours12,38 and an average initial moisture content of 94.71% w.b. was obtained gravimetrically.
2.2 System description and experimental procedure

Drying experiments were carried out with an active hybrid solar-electric dryer developed at Federal University of Technology, Owerri, Nigeria. The hybrid dryer (Figure 2) mainly comprises an Arduino microprocessor (Arduino Mega 2560, Milan, Italy) which controls the entire activity of the dryer system and automates functions such as temperature and humidity regulation, product sample mass loss, and electrical energy consumption (from AC and DC sources). The system also contains a main heating element powered by alternating current (AC) from the Public Power Supply or an electricity generating set. Transducers (for recording both temperature and relative humidity) were placed at five strategic points on the hybrid dryer viz: chimney, upper and lower drying racks, solar collector, and inlet fan, where measurements were taken automatically by the Arduino microprocessor unit and displayed on the liquid crystal display (LCD). With a 4x4 matrix keypad, different drying temperatures and air velocities were designated. The basic drying air parameters (temperature and relative humidity) were displayed on the LCD for the upper and lower drying racks, solar collector, chimney, and ambient environment. In the drying chamber, the drying racks were rigidly suspended on a weighing balance (which recorded the sample weight loss through the use of a weight sensor) attached to a flat iron bar. A 1500 W resistance wire supplied electrical heat to the drying chamber at preset air temperatures; whereas a Pyranometer (Apogee MP-200, Florida) was used to measure the quantity of solar radiation incident on the solar collector. The control unit and its accessories as well as other instrumentations were powered by a 75 Amps, 12 V accumulator, which were simultaneously charged by a 80 W solar panel; whereas the resistance wire was powered by an AC from the National grid. The energy consumption from the accumulator and AC were measured and recorded by the control unit.
Drying experiments were conducted at varying air velocities (0.5, 1.0, and 1.5 ms\(^{-1}\)), slice thicknesses (10, 15, and 20 mm) and air temperatures (50, 60, and 70°C). The dryer was turned on and the preset air velocity and drying air temperature were selected using the matrix keypad on the control panel (S/N 14). A steady-state conditioned was sustained for 10 minutes in the drying chamber. The sliced tomato samples (in drying racks) were introduced in thin-layer orientation. Losses in the sample mass were recorded through the use of a weight sensor attached to each of the weighing balance suspending the drying racks in the drying chamber. The Arduino program enables the weight sensor to convert the measured sample weights (in the drying racks) by the analog weighing balance into binary digits and stored in the microprocessor memory. The Arduino microprocessor automatically turned off the heating element when the optimum drying air temperature was reached in the drying chamber and switched it on again when the drying chamber air temperature goes one degree below the preset air temperature. The electrical and solar energy used for each batch size at different sample slice thicknesses, air temperatures and air velocities as well as drying rate and duration were measured. The experiment was repeated three times for a batch size of 1800 g and drying was terminated when there was no observable change between two consecutive sample mass measurements.

2.3 Experimental design

A three-factor and three-level (\(3^3\)) Box-Behnken method of Design Expert statistical tool was applied in the design and analysis of the drying experiments as well as determination of the relative effects of the three process/independent variables: air velocity (ms\(^{-1}\)), sample slice thickness (mm), and air temperature (°C) to response variables (energy requirements and drying duration). Analysis of variance (ANOVA) was carried out to determine the influence of the process parameters on the measured parameters at 1% and 5% levels of probability. Fishers test for least significant difference (LSD) was applied to compare differences in parameters, and where significant differences occur, the Duncan multiple range test (DMRT) was used to separate the treatment means. The accuracy of the energy model was checked against the normal probability residual plots, the predicted vs experimental plots as well as the values of the coefficient of determination (\(R^2\)).

2.4 Energy requirements

The total energy (\(E_t\)) and specific energy requirements (\(E_{kg}\)) for drying 1800 g batch of tomato samples of varying slice thicknesses, drying air temperatures and air velocities were measured by the Arduino microprocessor and calibrated using Equations (1) and (2)\(^7\),\(^13\),\(^34\):

\[
E_t = A_s \cdot V \cdot \rho_a \cdot C_{pa} \cdot \Delta T \cdot D_d
\]

\[
E_{kg} = \frac{E_t}{W_o}\]

2.5 Determination of activation energy for moisture diffusion

The plot of moisture ratio (MR) with drying time was used to represent the experimental data of the studied sliced tomato batch samples, since the initial value for MR = 1 for each of the experiments, the drying process of tomato slices in a hybrid solar dryer will be better explained by MR-curves than moisture content curves\(^7\),\(^35\). MR for tomato was calculated from Equation (3) as:

\[
MR = \left( \frac{M_t - M_e}{M_0 - M_e} \right) = e^{-kt}
\]

Moisture transfer (water transport) during drying was defined using the second law of diffusion of Fick, as outlined in Equations (4a) and (4b)\(^1\),\(^7\),\(^34\):

\[
MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi} e^{\left( \frac{-x^2}{4Dt} \right)}
\]

\[
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\]
\[ \ln (MR) = \ln \left( \frac{8}{\pi} - \frac{\pi^2 D_e t}{L^2} \right) \]  (4b)

The \( D_e \) was obtained with using the slope technique as given by Zielinska and Markowski,\(^{39}\) Afolabi et al.,\(^{34}\) and Beigi.\(^7\) A straight line was obtained when \( \ln (MR) \) was plotted against drying duration \( t \) at 50°C, 60°C, and 70°C air temperatures and 1.0 ms\(^{-1}\), 1.5 ms\(^{-1}\), and 2.0 ms\(^{-1}\) air velocities at constant slice thickness. The slope (coefficient \( k_1 \)) of the regression line is related to the effective moisture diffusion coefficient \( (D_e) \) of the sliced tomato sample to be determined by substituting into Equation (5) as:

\[ k_1 = \frac{\pi^2 D_e}{4L^2} \]  (5)

The activation energy \( (E_a) \) was calculated by using an Arrhenius type expression (Equation 6). The plots of \( \ln (D_e) \) against \( T_{abs}^{-1} \) gave a linear function expressed as Equation (7):\(^7,34:\)

\[ D_e = D_0 e^{-\frac{E_a}{R_g T_{abs}}} \]  (6)

\[ \ln D_e = \ln D_0 - \frac{E_a}{R_g T_{abs}} \]  (7)

When \( \ln (D_e) \) was plotted against the inverse of \( R_g \cdot T_{abs} \) on a semilogarithmic co-ordinates, it gave a straight line. The slope of the straight line, \( k_2 \) represents the activation energy, \( E_a \) of sliced tomato samples as expressed in Equation (8):

\[ k_2 = \frac{E_a}{R_g} \]  (8)

The coefficient of determination \( (R^2) \) was got by appropriating Equation (8) into the experimental data using linear regression using Minitab version 17 statistical tool.

### 2.6 Determination of quality parameters of tomato slices

#### 2.6.1 Lycopene content

Lycopene content, \( L_C (mg/100 g) \) in the fresh and dried samples was determined using the method of Ranganna.\(^{40}\) Ten grams (10 g) of dried tomato sample was crushed to powdery form and gently mixed with 15 mL of petroleum ether using Whatman filter paper. The lycopene pigment was diluted with acetone (lower phase) with water containing 5% Na\(_2\)SO\(_4\) and transferred into petroleum ether in a separating funnel, which was inverted and shaken for 45 seconds. Water from tomato samples was removed by this process, which yielded a stable lycopene emulsion and petroleum ether. The acetone at the lower phase was discarded and the top phase of petroleum ether having dissolved lycopene pigment was washed in a volumetric flask with distilled water poured into an amber color bottle containing about 5 to 10 g of anhydrous Na\(_2\)SO\(_4\) and left for 45 minutes. The petroleum ether was decanted using cotton wool and funnel. The Na\(_2\)SO\(_4\) slurry was washed with petroleum ether until no color was formed, and was transferred into a 50 mL volumetric flask. A spectrophotometer (accuracy ±0.0001 Abs units at 503 nm) was used to measure the absorbance. The value of \( L_C (mg/100 g) \) sample was calculated using Equation (9):\(^{26}\)

\[ L_C = \frac{31.206 \times \text{Abs}_{503 \text{ nm}}}{W_s} \]  (9)

#### 2.6.2 Ascorbic acid content

The ascorbic acid content, \( A_a, (mg/g) \) of the fresh and dried tomato samples was determined volumetrically using the method described in Abano et al.\(^{26}\) \( A_a \) was calculated using Equation (10):

\[ A_a = \frac{0.5 \times 50 \text{ ml} \times V_2}{5 \text{ ml} \times V_1 \times W_t} \]  (10)
2.6.3 | Brownian index

Brownian index (BI) is one of the quality parameters in dried tomato apart from color and flavor. It is used to assess the thermal effect of the drying air on the resulting product. Nonenzymatic browning (Brownian index) denotes the degree of brown color and known as a vital quality parameter related to browning. The procedure described in was adopted in determining the BI of the dried sliced tomato samples. Two grams (2 g) of ground dried samples were mixed with 50 mL 60% ethanol (v/v) and properly stirred. The mixture was kept for 12 hours, vigorously shaken and filtered. The absorbance of the filtrate was measured with a spectrophotometer. This value showed the extent of browning of the dried samples measured as absorbance at 440 nm (spectrophotometric approach). This procedure was replicated three times. BI was calculated after drying using Equation (11a) with x expressed as Equation (11b):

\[
BI = \frac{100(x - 0.31)}{0.17} (11a)
\]

where:

\[
x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a - 3.012b^*)} (11b)
\]

2.6.4 | Color content

Color change is another important quality attribute of dried products. It is a measure of the intrinsic quality of fruits and vegetables to most consumers. Universally, color has been associated with acceptability of food products. Increased brightness values (L*) and ratio of redness to yellowness (a*/b*) are required for general acceptability. Measurement of the fresh and dried sliced tomato color was done using the Hunter laboratory parameters to an accuracy of ±0.01 with automatic color differential meter (DC-P3, China) as described by. The color parameters were expressed in terms of L (whiteness/darkness), a (redness/greenness), b (yellowness/blueness). The color brightness coordinate, L*, measured the whiteness or darkness values of the sliced tomato samples which ranges between 0 (black) and 100 (white). The Hunter “a*” value or chromaticity ordinate was rated on a scale of -60 to +60: it measured red when positive and green when negative. The chromaticity coordinate, b* was also rated on a similar scale with -60 donating blue and +60 denoting yellow. This method was also adopted by References 26,36,37 in determining the colors of fresh and dried tomato and okra slices.

2.7 | Optimization of drying parameters

Response surface optimization was carried out using the numerical optimization approach. Desired goals (minimization of specific energy requirements and drying time as well as maximization of nutritional quality of dried samples) were used to perform optimization of process parameters and the response. A total desirability function/index, \(F_d\) was used and expressed as Equation (12): 26,37:

\[
F_d = (R_1x R_2x, \ldots, R_n)^{\frac{1}{n}} (12)
\]

\[0 \leq F_d \leq 1;\] with 0 and 1 being the minimum and maximum desirable coded levels, respectively. Desirability function indicates how well suited or favourable the experimental response is at a specified input variable stage. The high value of \(F_d\) illustrates the best functions of the drying system, which is taken as the optimal system solutions. The optimum factor values were determined from individual response variables that maximize \(F_d\).

3 | RESULTS AND DISCUSSION

3.1 | Effect of drying parameters on energy requirements and drying time

The Box-Bekhen approach was used to obtain the experimental results of the response variables. Their estimated influence on input process variables and interactions between the variable were stated in this section. The energy requirements
were obtained by multiplying the total power consumed by the measured time (30 minutes) as recorded by the Arduino microprocessor. A comparison was made between this energy value and that obtained from Eq. (2), and was found to be less by an average of 4.2%. This difference was attributed to constant air density and air velocity used in Equation (2), whereas for the system-measured values, varying air velocities were considered and air density changed with drying air temperature. Thus, the 4.2% difference between the system-measured and calculated energy value was neglected. The total and specific energy requirements for drying a batch of 1800 g of the sliced tomato samples at each dryer condition were determined using Equations (2) and (3). Figures 3 and 4 illustratively show that the total and specific energy requirements of tomato slices in a hybrid solar electric-assisted crop dryer varied from 7.82 to 125.48 kJ h\(^{-1}\) and 6.70 to 179.83 kJ h kg\(^{-1}\), respectively.

From Figures 3 and 4, the total and specific energy requirements increased with increase in air velocity and slice thickness at constant air temperature, and decreased with increasing air temperature and slice thickness at constant air velocity. Increasing the drying air temperature and air velocity, the average total and specific energy requirements reduced as a result of greater heat transfer rate and water pressure deficit which occurred in the drying samples and more convective hot drying air flowed across the sample surface and reduced the distance to capillary transport in order to increase the sample kinetic energy for rapid internal moisture diffusion and surface evaporation.\(^{41}\) Drying a thicker sample layer at constant air temperature and varying air velocities increased the total and specific energy requirements. This was as a result of additional drying time consumed by the thicker sample to release product moisture to the surface for eventual moisture evaporation by a convective airstream, which increased drying duration as well as total and specific energy requirements. Increasing the drying air temperature at reduced slice thickness required less total and specific energy to be consumed, since more product internal water is released at increasing drying air temperature, thus decrease in the drying time. Drying time was greatly reduced, thus gross reduction in energy requirements. Similar trends were observed in the works of.\(^{12,13,42}\) The maximum and minimum energy requirements were obtained in the treatments combinations of \(T_{50}, S_{20mm}, A_{2.0ms^{-1}}\) and \(T_{70}, S_{10mm}, A_{1.0ms^{-1}}\), respectively. At the thickest slice sample of 20 mm, more energy was required to transfer heat to the sample intercellular region due to higher capillarydistance. Convective hot, air at lower speed had more resident time in the drying chamber to pick up sample moisture than air at higher velocity, which causes turbulence at the dryer plenum.
**FIGURE 5** Effect of air temperature, air velocity, and sample thickness on drying duration of tomato slices at varying drying air temperatures ($T_{50}$, $T_{60}$, and $T_{70}$), air velocities (1.0, 1.5, and 2.0 m s$^{-1}$), and slice thicknesses (10, 15, and 20 mm).

![Graph showing drying time vs. air temperature and velocity with slice thicknesses 10mm, 15mm, and 20mm.

**TABLE 1** Analysis of variance (ANOVA) for energy requirements at varying drying conditions

| Source of variation | Degrees of freedom | Sum of squares | Mean square | F-value | P-value (Prob > F) | % contribution |
|---------------------|--------------------|----------------|-------------|---------|-------------------|----------------|
| $T$ — Temperature   | 1                  | 5820.30        | 5820.30     | 1.74    | .0002**          | 40.21          |
| $S$ — Slice thickness| 1                  | 2340.59        | 2340.59     | 32.35   | .0005**          | 38.77          |
| $A$ — Air velocity  | 1                  | 783.29         | 783.29      | 14.21   | .0392*           | 19.82          |
| $T \times S$        | 1                  | 308.25         | 308.25      | 3.18    | .001**           | —              |
| $T \times A$        | 1                  | 212.65         | 212.65      | 1.01    | .0701 ns         | —              |
| $S \times A$        | 1                  | 73.02          | 73.02       | 2.26    | .0214*           | —              |
| $T \times S \times A$| 2                  | 97.4           | 48.7        | 0.87    | .3172 ns         | —              |

Note: ** and * = significant difference at $P < .001$ and $P < .05$, respectively; ns = to not significant difference.

However, drying duration is a major determinant of crop energy requirements since moisture diffusion and surface evaporation are functions of duration of the samples in a convective air stream. Figure 5 illustrates the variations of drying duration as a function of varying air temperatures, air velocities, and sample thicknesses. Drying air temperature and slice thickness had significant treatment effect ($P < .01$ and $P < .05$) on the drying time of tomato slices in the dryer, whereas air velocity was significant at $P < .05$. Results of statistical analysis conducted revealed that air temperature had higher effect on the drying duration than slice thickness and air velocity. Drying duration reduction was necessitated by a corresponding increase in the air temperature at decreasing slice thickness and air velocity. This decrease could be due to high heat transfer gradient between the drying air (at increased air temperature) and the tomato slices and the decreased distance of capillary transport of internal water, which enhanced surface evaporation. The works of Akpinar$^{30}$ on pepper slices, Darvishi et al.$^{12}$ on potato slices, and Azadbakht et al.$^{42}$ on eggplant slices corroborated this observation. The drying of tomato slices varied from a minimum time of $150 \pm 15$ minutes ($70^\circ$C, 1 m s$^{-1}$, 10 mm) to $360 \pm 25$ minutes ($50^\circ$C, 2 m s$^{-1}$, 20 mm) for the range of the experimental variables. The relationship between drying duration and TSA-variables are expressed in Equation (13) as:

$$D_d = 72.31 e^{\left(1.35S^{3} + \frac{171.72}{AT^{1.5}}\right)} \quad [R^2 = 0.9883]$$

Table 1 presents the analysis of variance (ANOVA) for the effects of air temperature ($T$), slice thickness ($S$), and air velocity ($A$) on the energy requirements of tomato slices. The parameters $T$, $S$, and $A$ were statistically significant at $P < .05$ with different percent levels of contribution to energy requirements. Air temperature had the highest percent contribution to energy requirements (40.21%), followed by sample thickness (38.77%) and lastly air velocity (19.82%). This supports the observations of Nwakuba et al.$^{10}$ that drying air temperature chiefly controls the performance of convective hot air crop dryers as greater proportion of the energy requirements is used in raising the drying air temperature above ambient in order to increase its moisture-carrying capacity and initiate initial product mass diffusion.

Air temperature ($T$), slice thickness ($S$), and air temperature-slice thickness ($T \times S$) interaction had significant effects on energy requirements at 1%, whereas air velocity ($A$) and slice thickness-air velocity ($S \times A$) interaction had significant effects on energy requirements at 5% level of probability. The interaction effects of $T$-$S$-$A$ and $T$-$A$ parameters were not
significant at both levels of probability. The LSD of the means were tested using the Duncan’s new multiple range test (DNMRT) to determine which treatment mean was different from others. The result revealed the effect of slice thickness on energy requirements at varying air temperatures. The maximum and minimum energy requirements were obtained at $T = 50^\circ$C, $S = 20$ mm, and $T = 70^\circ$C, $S = 10$ mm, respectively. The effect of slice thickness on energy requirements at varying air velocities indicated maximum energy requirements occurred at $A = 2$ m s$^{-1}$ and $S = 20$ mm; whereas the minimum energy requirements occurred at $A = 1$ m s$^{-1}$ and $S = 10$ mm. Similar results were reported in the works of Azadbakht et al$^{42}$ for eggplant slices; Afolabi et al$^{34}$ for ginger slices; Nazghelichi et al$^{23}$ for carrot cubes; El-Mesery and Mwithiga$^{43}$ for onions slices; Akpinar et al$^{30}$ for pepper slices.

A multivariate equation describing the relationship between energy requirements and the drying parameters of $T$, $S$, and $A$ was obtained as expressed in Equations (14):

$$E_r = 1.02 e^{\left(\frac{0.25T + 0.75S}{5}\right)} \quad [R^2 = 0.9927]$$

(14)

The value of coefficient of determination ($R^2 = 0.9927$) indicates strong correlation between energy requirements and drying parameters. A regression analysis was performed to establish the validity of the relationship. The suitability of the model was validated with the normal probability plot of the specific energy requirements residuals as well as the predicted vs experimental specific energy requirements plot (Figure 6A, B, respectively). The closeness of the plotted data to the line (Figure 6B) is an indication of parity between the predicted and experimental energy requirement values and demonstrates that there was no question between the normality and the frequency of the outliers in the experimental data.$^{26}$ However, the resulting relationship is expressed in Equation (15) as:

$$E_{pr} = 0.839E_{ex} + 4.257 \quad [R^2 = 0.9962]$$

(15)

### 3.2 Activation energy for moisture diffusion

The activation energy for moisture diffusion, $E_a$ was obtained by fitting the moisture diffusivities values to Equation (7). A high coefficient of regression, $R^2$ (ranging between 0.9849 and 0.9939) was obtained from the linear relationship between
reciprocal of air temperature and \( \ln(D_e) \) (Figure 7), which showed that the fitting was a good quality. The \( E_a \) values calculated from Equation (8) (from the slope of the lines) were found to be in the range of 20.26 to 39.35 kJ mol\(^{-1}\) at air temperatures of 70°C and 50°C, respectively. From Table 2, \( E_a \) decreased with increasing air velocity at constant slice thickness and increased with increasing slickness at constant air velocity due to rise in the rate of surface water evaporation that increased the rate of heat transfer which in turn increased the kinetic energy of the capillary moisture for rapid diffusion. With increasing slice thickness, more energy was required to overcome the barrier for moisture diffusion.

By increasing the air velocity at constant drying air temperature, sample water molecules engaged in rapid collision, thereby increasing the average heat energy and reducing the \( E_a \). The maximum and minimum \( E_a \)-values (39.35 and 20.26 kJ mol\(^{-1}\), respectively) were obtained at slice thicknesses and air velocities of 20 mm, 1.0 ms\(^{-1}\) and 10 mm, 2 ms\(^{-1}\), respectively. The range of \( E_a \) values for tomato from this study are within the range of \( E_a \) for food materials (12.7-110 kJ mol\(^{-1}\)) as reported by Doymaz,\(^{44}\) Abano et al.,\(^{1}\) Afolabi et al.,\(^{34}\) and Sadin et al;\(^{45}\) and somewhat close to that (22.12-35.31 kJ mol\(^{-1}\)) obtained for tomato samples dried in an infrared hot air dryer at a constant air velocity of 1.1 ms\(^{-1}\); 3 mm, 5 mm, and 7 mm slice thicknesses; and temperatures of 60°C, 70°C, and 80°C\(^{38}\); and 22.66 to 30.92 kJ mol\(^{-1}\) for apple slices.\(^{46}\) Similar results have been obtained for tomato slices using different dryer systems and at various air temperatures and air velocities.\(^{1,2}\) This study obtained \( E_a \)-values relatively lower than activation energies of 51.26 kJ mol\(^{-1}\) for drying of okra\(^{44,46}\); 46.86 kJ mol\(^{-1}\) for drying of Avishan, and 73.84 kJ mol\(^{-1}\) for drying of thyme.\(^{47}\)

### 3.3 Effects of drying parameters on dried product quality

#### 3.3.1 Lycopene content

Response surface plots (Figure 8A-C) depict the influence of drying parameters on lycopene content of tomato samples. Analysis of variance conducted showed an insignificant decrease \((P < .01\) and \(P < .05\)) in the lycopene content as air temperature increases. Increasing the slice thickness and air velocity had significant increase in the lycopene content at 1% and 5% probability levels, respectively. The lycopene content of the dried samples were compared with that of
FIGURE 8  Response surface plot showing effects of drying parameters on lycopene content A, slice thickness and air temperature at constant air velocity of 1.0 m s\(^{-1}\), B, air temperature and air velocity at constant slice thickness of 10 mm, C, air velocity and slice thickness at constant air temperature of 50\(^\circ\)C

Fresh tomato slices. The lycopene content increased significantly (at both probability levels) from 2.79 mg/100 g to 64.79, 68.14 and 71.20 mg/100 g when subjected to air temperatures of 50, 60, and 70\(^\circ\)C, respectively. The maximum lycopene content (75.8 mg/100 g) was obtained at 60\(^\circ\)C, 20 mm and 2 m s\(^{-1}\) drying conditions; whereas the minimum lycopene content (35.2 mg/100 g) was obtained at drying conditions of 70\(^\circ\)C, 10 mm, and 1.5 m s\(^{-1}\). These values of lycopene content were relatively higher than 61.23, 59.10, 60.88, and 65.28 mg/100 g for air temperatures ranging between 40 and 80\(^\circ\)C, respectively reported by Abano et al\(^1\) for tomato slices in a microwave dryer, and lower than 82.90 mg/100 g for tomato paste.\(^{48}\) Janghuet al\(^3\) reported lycopene value ranging between 7.51 and 9.42 mg/100 g for sliced tomato dried at 50, 65, and 80\(^\circ\)C in a vacuum dryer.
Figure 9 Response surface plot showing effects of drying parameters on ascorbic acid content. A, slice thickness and air temperature at constant air velocity of 1.0 m/s$^{-1}$, B, air velocity and air temperature at constant slice thickness of 10 mm, C, air velocity and slice thickness at constant air temperature of 50°C.

3.3.2 Ascorbic acid content

The parameters: $T$, $S$, and $A$ had significant influence ($P > .05$) on the ascorbic acid content (AA) of sliced tomato samples. Slice thickness and air velocity had significant statistical effects on the AA content ($P < .001$ and $P < .005$). Increasing the slice thickness reduced AA, whereas AA increased with increasing air velocity (Figure 9A-C). Reduction in AA content during drying of fruits and vegetables has been reported by Rao and Agarwal. Adam et al. reported that slice thickness of onion slices significantly affect its AA content. Similar results have been reported for okra slices and potato slices. This phenomenal change in AA content has been attributed to longer time of exposure to hot convective drying air at increasing slice thickness at constant air velocity. Contrarily, Mrad et al. reported that increase in air temperature (30-70°C) decreased AA content of pear during hot air drying. A comparable result was obtained in the reports of Erenturk et al. for dried rosehip at 50-80°C; 1.67 m/s$^{-1}$ and 0.005 kg moisture kg$^{-1}$ dry air constant air velocity and humidity.
ratio, respectively. The gross reduction in AA content of the tomato samples is attributed to oxidation reaction rather than thermal damage after comparison between the initial AA content of fresh tomato ($2.69 \pm 0.22$ mg/g) and the dried samples. The maximum ($3.73 \pm 0.22$ mg/g) and minimum ($1.48 \pm 0.22$ mg/g) AA contents were obtained at 70°C, 10 mm, 1.5 ms$^{-1}$ and 70°C, 15 mm, 2.0 ms$^{-1}$, respectively.

### 3.3.3 Brownian index

The influence of drying parameters (air temperature, slice thickness, and air velocity) on the BI is shown in Figure 10A-C. Increasing air temperature and slice thickness had more increasing effect on the rate of formation of brown pigment in the dried samples than air velocity. This trend agrees with the report of Abano et al. Formation of the brown pigment at varying air temperatures was compared with a fresh tomato sample and was found to be 0.4 (at 50°C, 15 mm, and 1.0 ms$^{-1}$) and 0.8 (at 70°C, 15 mm, and 2.0 ms$^{-1}$), whereas that of the fresh tomato was 0.039. Abano et al. obtained maximum and minimum BI of 1.3 and 0.45, respectively for dried tomato samples and 0.051 for fresh sample for air temperature range of 50-80°C.

### 3.3.4 Color change

The ratio of redness to yellowness decreased with increasing air temperature and increased with increasing slice thickness, whereas the brightness increased with increasing slice thickness and air temperature (Figure 11A,B). No significant effect was observed in the color change by air velocity (Figure 11C,D). This observation was based on the relatively constant brightness values of 70.29 to 70.76 (Figure 11C) and 70.16 to 71.83 (Figure 11D) at varying air velocity and constant slice thickness and air temperature, respectively. Brightness of the dried samples was improved when compared with the color values of the dried and fresh tomato ($L^*$: 38.56 ± 3.92) samples, whereas gross reduction in $a^*/b^*$ was observed in the dried samples when compared to the fresh ($a^*/b^*$: 0.662 ± 0.015). Brightness of dried samples greatly increased from 50.0 (at 50°C and 2.0 ms$^{-1}$) to 76.0 (at 70°C and 1.5 ms$^{-1}$) at constant slice thickness. The redness of the fresh tomato (28.46) was higher than the dried samples (26.42-20.37). The brightness values increased from 32.86 to 35.63. These observations were consistent with Abano et al. who reported that $L^*$ increased from 60.91 to 65.47 at a temperature range of 50 to 80°C at 7 mm slice thickness, whereas redness and yellowness values were 27.16 to 21.51, and 34.53 to 37.19, respectively. It is important to note that only air temperature and slice thickness treatment combinations had significant changes on the redness to yellowness ratio ($a^*/b^*$) of the sliced tomato samples (Figure 11A). The $a^*/b^*$-value decreased with decreasing slice thickness, and increased as the drying air temperature increases at constant air velocity. The maximum and minimum $a^*/b^*$-value of 0.85 and 0.52, respectively were obtained at 50°C, 20 mm, and 70°C, 10 mm air temperature and air velocity process parameters, respectively. The resulting color of the dried samples is however, attributed to carotenoid lycopene content of tomatoes which is responsible for the redness color.

### 3.4 Optimization of energy requirements and drying parameters

Design Expert statistical tool was used to affirm the optimal drying situations (Equation 12). The maximum simulated values of specific energy requirements, lycopene content, ascorbic acid content, nonenzymatic browning index, brightness, redness to yellowness ratio, and drying duration were: 172.85 kWh kg$^{-1}$, 73.316 mg/100 g dry matter, 3.084 mg/g, 0.675 absorbance units, 67.935, 0.82, and 257.044 minutes, respectively. These predicted response variables are close to their corresponding actual values: 179.82 kWh kg$^{-1}$, 75.8 mg/100 g dry matter, 3.7 mg/g, 0.8 absorbance unit, 75.8, 0.868, and 360 minutes, respectively. A maximum desirability of 0.642 was obtained for the responses. At 95% confidence level, the results were predicted and yielded optimal process conditions of 57.28°C, 14.08 mm, and 1.3 ms$^{-1}$ for air temperature, slice thickness, and air velocity, respectively. Air velocity parameter was statistically insignificant in attaining desirability index at 95% prediction interval (confidence level), and so Design Expert software generates a 3D response surface plot for two process parameters whose values have significant effect on the optimization result vs the desirability index. 

At these optimum conditions, the specific energy requirements, lycopene content, ascorbic acid content, nonenzymatic browning index, brightness, redness to yellowness ratio, and drying duration were obtained as $103.313 \pm 2.35$ kWh kg$^{-1}$, $58.7 \pm 2.19$ mg/100 mg dry matter, $2.9 \pm 0.26$ mg/g, $0.51 \pm 0.033$ absorbance unit, $60.074 \pm 1.44$, respectively.
FIGURE 10  Response surface plot showing effects of drying parameters on nonenzymatic browning index of tomato slices A, slice thickness and air temperature at constant air velocity of 1.0 m s$^{-1}$, B, air temperature and air velocity at constant slice thickness of 10 mm, C, slice thickness and air velocity at constant air temperature of 50$^\circ$C.

0.77 $\pm$ 0.021, and 61.88 $\pm$ 8.93 minutes, respectively. The surface plot of the desirability for the optimum conditions is shown in Figure 12. The optimum response values for the dried sample quality were close to that of\textsuperscript{23} and Abano et al.\textsuperscript{26} but varied in terms of drying duration due to differences in batch size and level of process parameters used.

4 | CONCLUSION

It is evident from this study that tomato fruit, as well as most dried food products should be produced under controlled process conditions, since the quality of the dried product is a function of numerous factors related to the parameters of the drying process. Thus, the market for dried tomato products has continuously demanded better quality products, which
FIGURE 11 Response surface plot showing effects of dying parameters on color change of tomato slices A, slice thickness and air temperature effect at 1.0 m s⁻¹ constant air velocity on redness to yellowness ratio, B, slice thickness and air temperature at 1.0 m s⁻¹ constant air velocity, C, air velocity and slice thickness at 50°C constant air temperature, D, air velocity and air temperature at 10 mm constant slice thickness

has led to this study. The process of moisture removal must be done in a way as to have least damaging effects on the nutritional and economic values of the dried tomato, thus need for optimization of process conditions. The justification of this study banks on the need to achieve significant energy savings during dehydration process of tomato slices and the concerns about its cost implications, influence on the food supply chain, environmental impacts and estimation of the optimum drying conditions most appropriate for a tomato crop, in order not to compromise its functional and sensory characteristics.

Within the range of experimental study, the total and specific energy requirements of tomato slices in a hybrid solar crop dryer varied from 7.82 to 125.48 kJ h and 6.70 to 179.83 kJ h g⁻¹, respectively. Air temperature and slice thickness
had significant treatment effects ($P < .01$ and $P < .05$) on the drying time, whereas air velocity was significant at $P < .05$. The drying duration varied from 50 ± 15 to 360 ± 25 minutes at drying conditions of 70°C, 1 ms$^{-1}$, 10 mm to 50°C, 2 ms$^{-1}$, 20 mm, respectively. The maximum and minimum activation energy ($E_a$) values of 39.35 and 20.26 kJ mol$^{-1}$, respectively were obtained at slice thicknesses and air velocities of 20 mm, 1.0 ms$^{-1}$ and 10 mm, 2 ms$^{-1}$, respectively. The energy requirement and drying duration models of adiabatic of drying process of sliced tomato samples were predictive, as they indicated $R^2$ values above 0.98.

Increase in slice thickness and air velocity significantly increased the lycopene content at 1% and 5% probability levels. Increasing the air temperature significantly increased the lycopene content from 2.79 mg/100 g to 64.79, 68.14, and 71.20 mg/100 g. The maximum lycopene content (75.8 mg/100 g) was obtained at 60°C, 20 mm, and 2 ms$^{-1}$; whereas the minimum lycopene content (35.2 mg/100 g) was obtained at drying conditions of 70°C, 10 mm and 1.5 ms$^{-1}$. Slice thickness and air velocity had significant statistical effects on the ascorbic acid (AA) content (at $P < .001$ and $P < .005$). The brightness of dried samples greatly increased from 50.0 to 76.0 at constant slice thickness. The redness of the fresh sliced tomato sample was higher than the dried sliced samples (26.42-20.37). The yellowness values increased from 32.86 to 35.63. The experimental results were predicted at 95% confidence level in the range of the process variables and yielded optimal process conditions of 57.28°C, 14.08 mm, and 1.3 ms$^{-1}$ for air temperature, slice thickness, and air velocity, respectively. At these optimum conditions, the specific energy requirements, lycopene content, ascorbic acid content, nonenzymatic browning index, brightness, redness to yellowness ratio, and drying duration were obtained as 103.313 ± 2.35 kW h kg$^{-1}$, 58.7 ± 2.19 mg/100 mg dry matter, 2.9 ± 0.26 mg/g, 0.51 ± 0.033 absorbance unit, 60.074 ± 1.44, 0.77 ± 0.021, and 61.88 ± 8.93 minutes, respectively.

Results of the optimal process parameters from this study's response surface methodology provide optimized drying conditions for better quality dried tomato to drying industries, as well as increase dryer energy efficiency for cost effective drying operation. Regarding future studies, an exergoeconomic analysis of the crop dryer with heat recovery and thermal storage systems, as well as numerical simulation of heat and mass transfer analyses of different geometries of tomato sample are proposed. It is also recommended to maintain ±0.1 of the optimum process conditions for economy.

**NOMENCLATURE**

$A$  
air velocity (ms$^{-1}$)

$A_s$  
sample plate area (m$^2$)

$a^*$, $a$  
redness of dried and fresh tomato samples, respectively

$Abs$  
absorbance

$b^*$  
yellowness of the dried samples

$C_{pa}$  
specific heat of air (kJ kg$^{-1}$ °C)

$D_{d}$  
drying duration (minutes)

$D_e$  
effective moisture diffusivity (m$^2$ s$^{-1}$)

$D_o$  
Arrhenius constant (or prelog, or frequency factor, m$^2$ S$^{-1}$)

$E_a$  
activation energy of diffusion of water (kJ mol$^{-1}$)
\( E_{kg} \) specific energy requirement (kJ kg\(^{-1}\))
\( E_{pr}, E_{ex} \) predicted and experimental specific energy requirements (kJ h g\(^{-1}\)), respectively.
\( E_r \) energy requirement (kJ)
\( E_t \) total required energy in each drying phase (kJ h\(^{-1}\))
\( F_d \) total desirability function/index
\( L \) half thickness of the sliced tomato samples (mm)
\( L^* \) lightness of the dried samples
\( M_e \) equilibrium moisture content (%db)
\( M_o \) initial moisture content (%db)
\( MR \) moisture ratio
\( M_t \) moisture content at any time
\( n \) total number of responses
\( R_g \) gas constant (8.3143 kJ mol\(^{-1}\) K)
\( R_1, R_2, R_n \) response variables
\( S \) slice thickness (mm)
\( T \) air temperature (°C)
\( T_d \) total drying duration of each sample batch (hours)
\( T_{abs} \) absolute temperature (°K)
\( t \) drying duration (minutes)
\( V_1, V_2 \) volumes of titrate (mL) from working standard solution and supernatant, respectively
\( V \) air velocity (ms\(^{-1}\))
\( W_o \) initial mass of sample (kg)
\( W_s \) weight of the sample (g)
\( \rho_a \) air density (kg m\(^{-3}\))
\( \Delta T \) temperature difference between ambient and hot air (°C)

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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