Energy requirements for drying of sliced agricultural products: A review

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Abstract: This work presented a review of energy requirement for drying sliced agricultural crops in order to produce high quality and shelf-stable products. Work on the estimation of energy requirement for drying different sliced crops such as potato, carrot, garlic, onions, mango, banana, apple, tomato etc. and factors affecting their energy requirement were reported. From the review, programming models for drying sliced fruits, as well as different empirical equations adopted by some researchers for estimating the energy requirements of different sliced crops at specific drying parameters were reported. Obtained results showed that crop functional characteristics, initial and desired moisture contents, slice thickness, air temperatures, specific heat capacity, relative humidity, and air velocity are the major parameters affecting sliced crop drying energy requirement. Generally, the minimum energy requirement for drying moisture-laden sliced crops like tomatoes, apples, carrot, mango, cucumber etc. were found to be between 4.22 and 24.99 MJ/kg water removed. Field test results by other researchers for different drying systems and crops were also presented. Prospects for future work were suggested.

Keywords: crop drying, sliced product, energy requirement, dryers, heat.

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1 Introduction

Drying has been and continues to be a major method of preserving agricultural products especially in developing countries like Nigeria. It is an integral part of agricultural processing and is usually the last step of operation before storage (Mu'azu et al., 2012). It is generally defined as the removal of moisture by heat from a substance which yields a solid product at an acceptable moisture level that prevents deterioration within a certain period of time for marketing, safe storage, processing, or transportation (Mu'azu et al., 2012; Ekechukwu and Norton, 1999; and Khouzam, 2009). Drying consists of the process of heat transfer to the product from the heating source, mass transfer of moisture from the interior of the product to its surface and from this surface to the surrounding air with the help of airflow. In other words, water is vaporized in the product matrix by heated air resulting in a phase change which involves high energy consumption and eventually gross product drying. With drying, weight and volume of products are reduced, packing and storage spaces are minimized, transport cost is lessened, and it enables the product to store well under ambient conditions (Ongen et al., 2005; Swamy et al., 2014).

Most agricultural products are characterized with high initial moisture content of about 70% to 90% (wb) at harvest. They are classified as highly perishable commodities which require to be dried to a safe moisture level of about 7% – 15% (wb) (depending on the crop variety, slice thickness, length of time in storage, storage structure, geographical location and product's end use) in order to obtain proper long term storage since the activities of the microorganisms, enzymes or ferments in the material have been suppressed (Arinze et al., 1990).

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As the result of this, considerable amounts of energy is required to heat the drying air so as to vaporize the internal water to the crop surface, and then to the ambient air. The theoretical energy for dehydration of sliced fruits and vegetables varies for each variety and that average of 1.5 x 10^6 kJ/t of water removed is required assuming the temperature of $50^{O}C$ is used (Energy Network, 2000). Sliced crop energy requirement for drying have been found to vary due to the type of crop, moisture content at harvest, desired moisture content, crop specific heat capacity, latent heat of vaporization of water, intended use, gross mass, size, shape, and biological characteristics such as surface texture, crop porosity, nutritional content, drying times, production capacity, drying temperatures as well as operating pressure and the efficiency of the drying equipment (Billiris et al., 2011; Raghavan et al., 2005; Planters Energy Network, 2000 and Gunasekaran and Thompson, 1986). Long drying periods tend to increase the energy requirement for the production of a unit dried product due to the gross mass of the product to be dried. This energy is the summation of the sensible and latent heat (to raise the material from ambient to drying temperature and heat needed to evaporate the moisture respectively) that enters the drying system. It is affected by mass flow rate of air, initial and final enthalpy of the ambient air, and drying time (Panchal et al., 2013). Due to the low thermal conductivity of food materials in the falling rate drying period, Motevali et al. (2014) surmised that heat transfer to the inner sections of food materials during conventional heating is limited. This phenomenon results in high energy requirement for drying. In order to circumvent this, Ohanwe and Sule (2007) posited that drying be done with sliced products so as to enhance the heat transfer rate in the food matrix by fully exposing each and every layer or kernel of the crop to the hot convective drying air. This has been found more convenient and effective with sliced crop thickness in terms of energy requirement and drying cost. Uniform drying, low energy consumption and decreased drying time are characterized with sliced product drying (Koyuncu et al., 2005; El-Mesery and Mwithiga, 2012; Panchal et al., 2013; Zarein et al., 2013, and Motevali et al., 2014). This is so because there is no finite moisture gradient through the drying layer(s). The minimum theoretical amount of energy required for drying sliced products in convective hybrid solar dyers ranges between 5.21 to 90.4 MJ/kg of water removed (Raghavan et al., 2005). This value, according to surveyed literature, is mostly affected by the amount of moisture to be removed. Nwakuba (2011) observed that the moisture ratio is directly proportional to the quantity of heat required to remove product moisture.

Energy requirement for sliced crop drying therefore, is important for the following major reasons: (i) in order to estimate the optimum quantity of temperature, air flow, and drying time most suitable for a particular sliced crop so as to avoid over drying which is consequent to undermining the nutritional value of the dried product; (ii) applied in the design of appropriate cost effective drying system which would consume minimum amount of energy to convey the required sensible and latent heat given the crop’s physical and biological characteristics; (iii) for simulation of drying systems. Therefore, with increasing pressures to reduce environmental degradation, both from the public and governments, it is necessary to improve drying processes to reduce its high energy requirement and greenhouse gas (GHG) emissions, while still providing a high quality product with minimal increase in economic input. This, in all, would reduce the cost of drying operation, enhance the crop shelf-life, product diversity, substantial volume reduction, availability and acceptance of dried sliced food products in the market at a reasonable price (El-Mesery and Mwithiga, 2012). Interestingly, some work has been done on the estimation and measurement of energy requirement for drying sliced crops like fruits, vegetables, root and tuber crops (Darvishi et al., 2013; El-Mesery and Mwithiga, 2012; Zarein et al., 2013). Different energy aspects of agricultural product drying techniques; dryer energy analysis and consumption (Koyuncu et al., 2005; El-Mesery and Mwithiga, 2012; Darvishi, 2012; Zarein et al., 2013), as well as advances in novel technologies to improve drying efficiency (Raghavan et al., 2005) which will help achieve the above goals have been proposed.

This work therefore, aims at reviewing the available reported work carried out by other researchers on energy requirement for drying sliced agricultural products irrespective of the drying method or type of dryer, with a view to point out the progress made so far as well as prospects, and make recommendations for further work.

2 Estimation of energy for sliced crop drying

Energy requirement for sliced crop drying is generally expressed as the amount of energy required per kilogram of water evaporated from a drying product during the drying process. Specific energy requirement is the ratio of the energy consumption/requirement to the initial mass of the dried sliced crop sample. The energy required for drying sliced foodstuffs mainly comprises the thermal energy required to remove water from the food material and the mechanical energy required for conveyance. This energy requirement may be higher than that required to vaporize free water -latent heat of vaporization due to the level of the initial moisture content of the material and the desired final moisture content level as well as the state of water to be removed from the foodstuff (Okos et al., 1992). The high energy requirement (for a crop with moisture content below 12% db) is as a result of the increase in the intra-particle resistance to moisture migration (Cenkowski et al., 1992). Okos et al. (1992) stated that energy increases as the binding force between water and the food increases. This energy requirement according to Rizvi (2005) has two major components: the energy required to evaporate free water and the energy required to remove water that is associated with the food matrix. This is a major function of the dryer design. Other factors associated with this are: the amount of moisture to be removed, environmental conditions during drying, and the efficiency of the dryer. This measure of energy requirement can be calculated by given the initial and final product moisture contents, the amount of moisture loss during product drying, latent heat of vaporization of water, enthalpy of the drying air, and the drying time (Ajiboshin et al., 2011). It is simply the minimum quantity of heat required to evaporate moisture per kilogram of a drying material: a summation of the sensible heat needed to raise the feed from ambient to drying temperature and the latent heat required to evaporate the moisture are expressed as Equation 1.

$$Q = [M.C_P.(T_2 - T_1) + (MR.\lambda)] \qquad 1)$$

Where: M = mass of feed (kg), C_P = crop specific heat capacity (kJ/kg^{O}C), T_2, T_1 = drying and ambient air temperature respectively (^{O}C), MR = moisture ratio, λ = latent heat of vaporization of water at T_2 (kJ/kg), $M.C_P.(T_2 - T_1) =$ sensible heat (kJ), $MR.\lambda =$ latent heat.

This minimum quantity of energy, Q (kJ/kg) can be broken down to amount of energy per kg of product by dividing by the mass of the product. It is also referred to as the minimum theoretical heat requirement which can be achieved by an adiabatic dryer. Although in reality, there is no drying equipment that can use the exact required quantity of heat to dry a product. This is because variations in the dryer design components, difference in crop biophysical characteristics and airflow influence the amount of energy to be consumed by the dryer.

Ehiem et al. (2009) estimated the actual quantity of heat energy required to dry sliced fruits and vegetables using Equation 2.

$$H_D = C_A T_C M_R \qquad (2)$$

Where: C_a = specific heat capacity of air = 1.005kJ/kg^{O}C; M_R = amount of moisture to be removed;

T_c = temperature difference in the dryer chamber, ^{O}C.

Okoroigwe et al. (2013) estimated the theoretical energy requirement for drying of sliced yam tubers in a hybrid solar-biomass dryer using the basic heat equation as given by Equation 3 as:

$$Q_W = 4.186M_W\left(597 - 0.56T_{pr}\right)\ (kJ) \qquad (3)$$

Where: M_W = Mass of moisture evaporated (kg), T_{pr} = product temperature which can be assumed as the ambient temperature at the coldest weather condition (^{O}C).

The implication of Equation 2 is that since fruits and vegetables are heat sensitive, the amount of water to be removed, the optimum drying temperature of the crop, and specific heat capacity of the drying air are to be considered in order not to denature the nutritive quality of the product through excess heat drying. While Equation 3 considers a heat balance between the ambient environment and the quantity of moisture removed to yield a stable product.

Minaei et al. (2011) estimated the energy for drying 1 kgof different slice thickness of a medicinal herbal plant – St. John's Wort (*Hypericum Perfoatum*) using a hybrid solar-biomass hot air-dryer. The minimum and maximum specific energy requirement for drying 1 cm of 1 kg layer sample of St. John's Wort were estimated as 5.31 and 26.06 kWh/kg using Equations 4 and 5.

$$E_t = A\upsilon\rho_a C_{pda}\Delta T t \qquad (4)$$

$$E_{kg} = \frac{E_t}{W_0} \qquad (5)$$

Where: E_t = is the total required energy in each drying phase (kWh), A, is the sample plate area (m^2), υ = air velocity (m/s), $\rho_{a\,=}$ air density (kg/m^3), t = total drying time of each sample (h), ΔT = temperature difference between ambient and hot air (℃), and $C_{pda\,=}$ specific heat of air (kJ/kg ℃); W_o = sample weight (kg).

Hafezi et al. (2015) estimated the energy requirement for drying potato slices using a vacuum-infrared dryer as given by Equation 5. The total required energy (kWh) was given as the sum of the power consumed by the pump and the energy consumed by the infrared lamp. Experiments were performed with the infrared lamp power levels 100, 150 and 200 W; absolute pressure levels 20, 80, 140 and 760 mmHg; and with three thicknesses of slices 1, 2 and 3 mm, in three repetitions. Results showed in Figure 1 indicate the amount of energy required by the vacuum-infrared dryer to dry potato slices. The use of vacuum in conjunction with infrared radiation drying increased the energy requirement in comparison to merely infrared drying. Increase in slice thickness and absolute pressure were found to increase the energy requirement, whilst increase in infrared power decreased the energy need for drying slice potato. The maximum and minimum energy requirement values were calculated (from Equation 5) to be 6.43 and 2.053 MJ for the infrared power of 100 W with absolute pressure level 760 mmHg (without acts of vacuum) at the slice thickness of 3 mm and the infrared power of 150 W with the absolute pressure of 20 mmHg at the slice thicknesses of 1 mm, respectively.

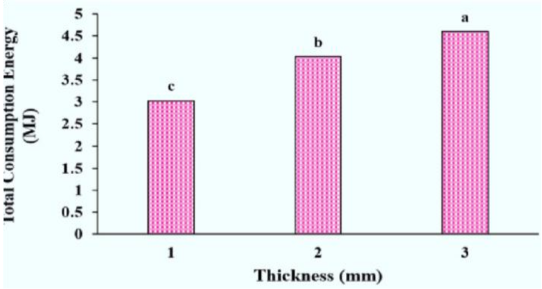


Figure 1a Effect of slice thickness on energy consumption of potato slices during drying process.

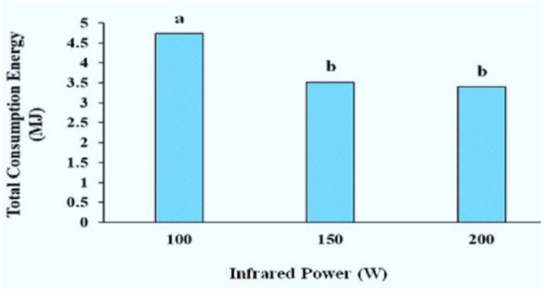


Figure 1b Effect of infrared power on the energy consumption of potato slices.

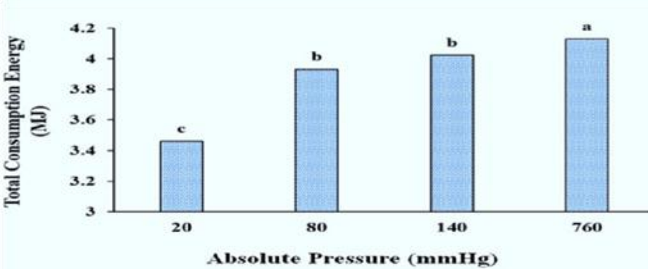


Figure 1c Effect of absolute pressure on the energy consumption of potato slices

Source: Hafezi et al. (2015).

It is induced from the foregoing that, reducing the infrared power, absolute pressure in the drying chamber and slice thickness of potato slices, will reduce the energy consumed during drying, which improve the product quality. Similarly, Tripathy, and Kumar (2009) in their work on energy analysis of solar drying of potato slices and cylinders, observed that the specific energy consumption for both sample geometries decreases exponentially with the drying time and moisture content. Also the thermal energy is predominantly required for moisture evaporation, which in turn depends on moisture content of the food sample at a given instant (Figure 2).

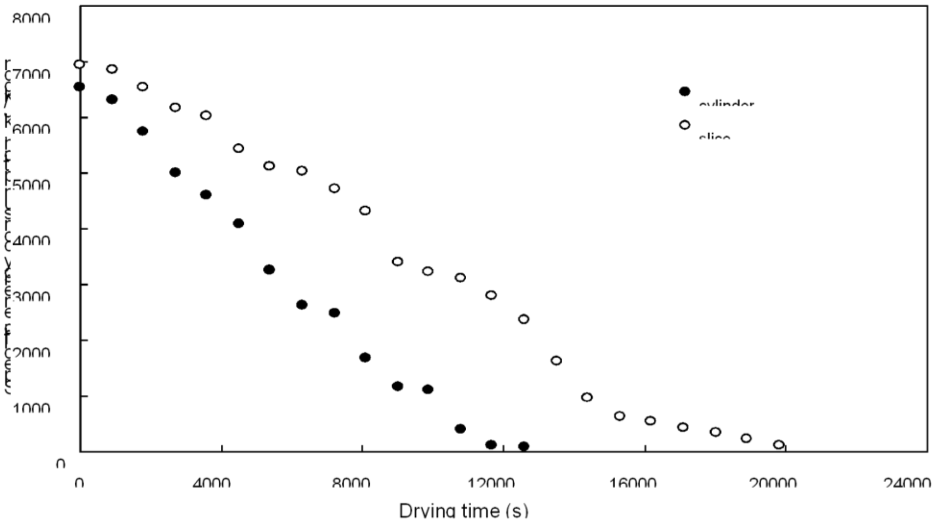


Figure 2 Variation of specific energy consumption with drying time for potato cylinders and slices.

Source: Tripathy and Kumar (2009).

The minimum specific energy required (E_P) was estimated as the sum of the energy required for sensible heating of the product from initial sample temperature, T_{po} to desired temperature, T_p and the energy required for the moisture evaporation from product moisture content, M to desired final moisture content, M_f expressed as Equation 6:

$$E_P = [1 + M(t)]C_P(t)[T_P(t) - T_{PO}] + \left[M(t) - M_f\right]\lambda(t) \tag{6}$$

Where: t = drying time (s), C_P = crop specific heat capacity (J/kgK), M = initial moisture content (% db), M_f = desired moisture content (% db), λ = latent heat of vaporization (kJ/kg), T_{PO} and T_P = initial and desired temperatures of product respectively (K).

As drying progresses, the moisture content of food product decreases, resulting in reduction of energy requirement. Higher values of specific energy consumption (SEC) in the initial stage of drying, known as constant-rate period, is due to faster moisture evaporation rate but it decreases rapidly in the later stage called the falling-rate drying period when the entire product surface is no longer wetted and the wetted area continually decreases until the surface is completely dry. In addition, it can also be seen (from Figure 2) that higher values of SEC are obtained for slices than cylinders during the entire period of drying. There is rapid mass evaporation of cylinders due to the higher surface heating effects resulting from more exposed area per unit mass leading to the lower specific energy consumption.

However, Figures 3a and 3b show the drying energy requirement and the effect of drying parameters on specific energy consumption of sliced herbal medicinal leaf (*Hypericum Perfoatum*) respectively. The plant, sliced in three thicknesses- t_1, t_2, and t_3 (as shown in Figure 3a) was subjected to four drying temperatures- T_{40} °C, T_{50} °C, T_{60} °C, and T_{70}°C at three different air velocities- $A_{0.3}$, $A_{0.7}$, and $A_{1.0m/s}$. At higher temperatures, drying time decreases due to increasing thermal gradient inside the substance and consequently increasing the drying rate. Also, drying time decreases with increasing air velocity. This is because vapour pressure decreases with increasing air velocity, thus, the product moisture would encounter less resistance on its way out and exits at higher rate. These observations were similar to the results reported previously (Motevali et al., 2011) which are plausible. With increasing product layer thickness in the dryer, the drying time and hence the required energy for drying increases.

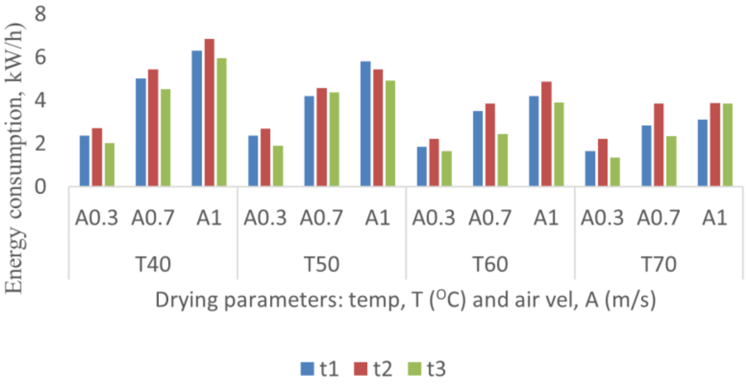


Figure 3a Energy consumption for drying different thicknesses (t_1, t_2, t_3) of *Hypericum Perfoatum* at different air temperatures and velocities (Minaei et al., 2014).

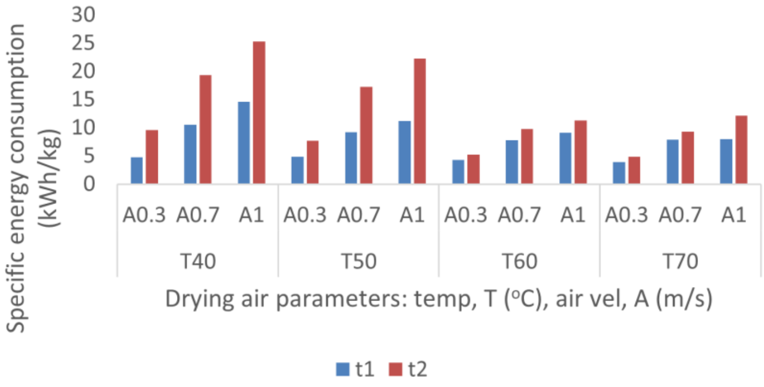


Figure 3b Effects of drying air velocity (A) and temperature (T) on specific energy consumption for drying 1 cm (t_1) and 2 cm-thick (t_2) layer of Hypericum Perfoatum (Minaei et al., 2014).

Generally, increase in the air velocity at constant air temperature and slice thickness, increases the energy requirement. This implies more rotation of the air-moving device, hence more energy. This is so because the drying air does a lot of work to overcome the mass diffusion of internal water and consequent surface evaporation. Also, increase in air temperature increases the energy requirement; since more kWh of energy will be supplied to the heating units of the drying system to raise the air temperature above ambient. The specific energy at a given temperature increases with air velocity while it decreases with increased temperature for a constant air velocity. However, the maximum and minimum energy consumption were obtained at air velocity of 1 m/s and temperature of 40^{o}C, 0.3m/s and 70^{o}C respectively, whilst for the specific energy consumption, the maximum and minimum values were obtained at 1 m/s, 40^{o}C, and 0.3m/s, 70^{o}C respectively. This indicated that drying air temperature remains the pivot for convective hot air dryers. Also, the minimum and maximum values of the required specific energy for drying a 1 cm, 2 cm, and 3 cm layers sample (at different temperatures and air flow velocities) were 5.31 and 26.06 kWh/kg, 4.41 and 17.53, and 4.28 and 13.67 kWh/ kg respectively. The energy requirement decreases with increasing layer thickness from 1 to 2 cm and from 2 to 3 cm, such that at a given air temperature and velocity, the maximum specific energy is associated with the 1 cm thick layer. This is because with increasing material thickness, sample weight in the dryer also increases. Specific energy is thus calculated by substituting the value of the required energy obtained from Equation 4 as well as the sample weight (at various thicknesses) into Equation 5 above.

Afolabi et al. (2014) estimated the drying energy requirement for ginger slices (cut into 5, 10, and 15 mm slices, air temperatures from 40 ℃ to 70 ℃, and air velocity of 1.5 m/s in a convective electric dryer) using Equations 4 and 5. From the results obtained (Figure 4), the total needed energy (Figure 3a) varied from 735.3 to 868.5 kWh, the lowest value was obtained with ginger slices of 5 mm thickness at a drying air temperature of 70 ℃ and the highest value was from ginger slices of 15 mm thickness at 60 ℃.

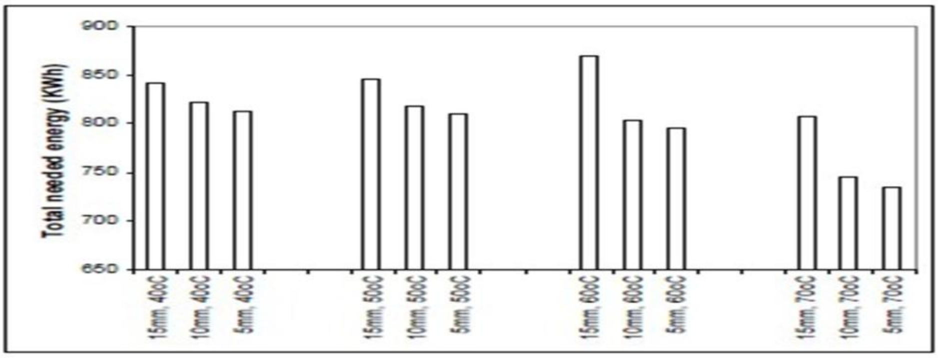


Figure 4a Total energy requirement for drying ginger slices (Afolabi et al., 2014).

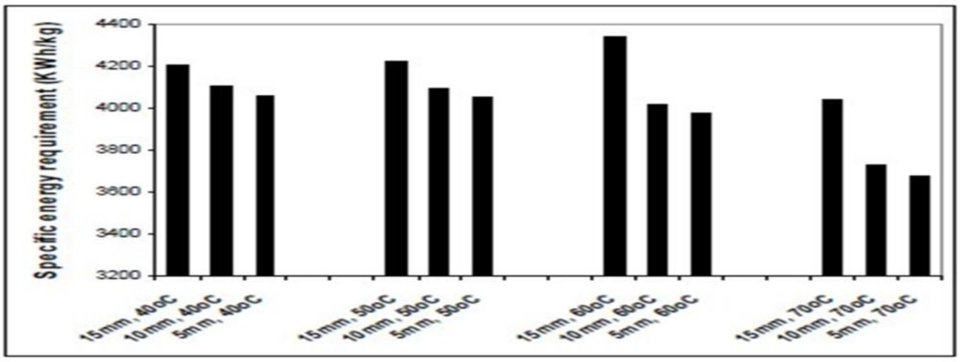


Figure 4b Specific energy requirement for drying ginger slices (Afolabi et al., 2014).

The maximum and minimum values of specific energy requirement (Figure 4b) of 4342.4 and 3676.6 kWh/kg for sliced ginger drying were obtained at a temperature of 60 ℃ and 70 ℃ respectively. The highest total energy needed was obtained for thickest samples (i.e.15 mm) and the lowest was for 5 mm samples. This is due to the fact that the energy utilized to transfer heat to the internal regions of the 15 mm slice is higher since the heat transfer distance is longer. This will result in a longer drying time (since it is dependent on the drying time as indicated in Equation 4). The lowest total energy needed and minimum value of specific energy requirement was obtained from samples dried at 70℃. This is probably as a result of the greater heat transfer and water vapour pressure deficit that occur when drying is done at higher temperatures (Rayaguru and Routray, 2012). This gives rise to a greater uptake of air and evaporation is achieved in a shorter time thus reducing the amount of energy needed.

Sarsavadia (2007) determined the total energy requirement for drying onion slices using a flat plate solar-assisted dryer with air heater having both the corrugations and triangular fins on the absorber plate. The obtained results revealed that the energy required per unit mass of water removed during drying from initial moisture content of about 86% (wet basis) to final moisture content of about 7% (wet basis) without using recirculation of air was between 23.548 and 62.117 MJ/kg water. Similarly, Weiss and Buchinger (2010) studied the energy requirement for selected sliced crops as shown in Table 1.

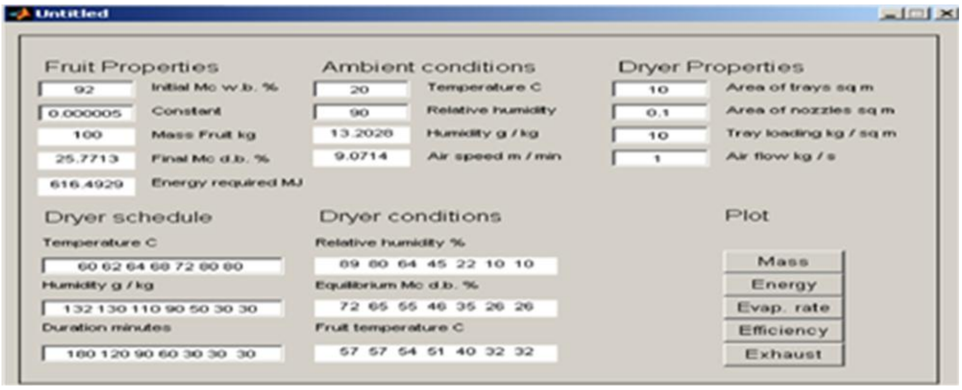
Table 1 Sliced crop data on solar drying potential

Sliced crop	Initial moisture content, %wb	Final moisture content, %wb	Energy required MJ/kg	Max. temperature ^{O}C	Required drying temp ^{O}C	Required drying time
Apple	80 -85	20 – 24	1.502	70	45	6 h
Banana	70 – 80	7 – 15	1.679	70	45	8 h
Cassava chips	62 – 75	14 – 17	1.105	150	30 -60	92 h
Pepper	75 – 80	5 – 14	1.61	90	40	5 -6 h
Mango	80 -85	12 – 18	1.564	70	55	1–2 weeks
Potato	70 – 75	8 – 13	1.453	75 – 85	50 – 70	Several days
Tomato	75	35	0.963	75	30 - 60	36 h

Note: Source: Weiss and Buchinger (2010).

From Table 1, sliced potato takes several days to dry while sliced banana takes few hours, yet they have same range of initial and final moisture contents. This is because, the microcellular structure of potato slices has strong/high intra-particle resistance to moisture migration which slows the rate of drying. Whereas, banana matrix with high initial moisture content poses little resistance to mass diffusion of internal water, hence few hours of drying is required. Increasing the energy requirement of potato slices to that of banana slices implies a proportional reduction in temperature (the key drying parameter) which results in low thermal efficiency of the drying system. Alternatively, air velocity can be increased at constant drying temperature in order to reduce the vapour pressure, thus the product moisture would encounter less intra-particle resistance as it migrates at higher rate. This implies fewer days of drying. On the other hand, apple and mango slices with similar energy requirements (1.5MJ/kg) have different drying time of 6 h and 1 – 2 weeks respectively because of their different final moisture content of 20% - 24% wb and 12% - 18% wb respectively. With the same energy requirement, it will take longer time to dry from 20% – 24% wb to 12% -18% wb since their initial moisture contents are the same.

Abdulla et al. (2011) developed an energy prediction model for sliced fruit drying in a fluidized bed dryer using Mat lab software. The major parameters of the model considered are shown in Figure 5.



Fruit Properties

92 Initial Mc w.b. %
0.000005 Constant
100 Mass Fruit kg
25.7713 Final Mc d.b. %
616.4929 Energy required MJ

Ambient conditions

20 Temperature C
90 Relative humidity
13.2028 Humidity g / kg
9.0714 Air speed m / min

Dryer Properties

10 Area of trays sq m
0.1 Area of nozzles sq m
10 Tray loading kg / sq m
1 Air flow kg / s

Dryer schedule

Temperature C
60 62 64 68 72 80 80
Humidity g / kg
132 130 110 90 50 30 30
Duration minutes
180 120 90 60 30 30 30

Dryer conditions

Relative humidity %
69 80 64 45 22 10 10
Equilibrium Mc d.b. %
72 65 55 46 35 26 26
Fruit temperature C
57 57 54 51 40 32 32

Figure 5 Window of the developed model using Mat lab (Abdulla et al., 2011).

The results of their experimental study revealed that the operating parameters and air conditions highly influenced energy requirement for drying: the lower the ambient air temperature is, the more energy that is required to dry the fruit (Figure 6a) would be. Increase in air speed and/or temperature highly reduced the energy required. This, however, applies to all moisture-laden sliced crops such as tomatoes, mango, apple, etc., in other words, high reduction in cost can be achieved. Whereas changes in relative humidity of the ambient air do not affect the energy requirement of the dryer. Figure 6b shows the energy requirement for the dryer due to different airflow rates.

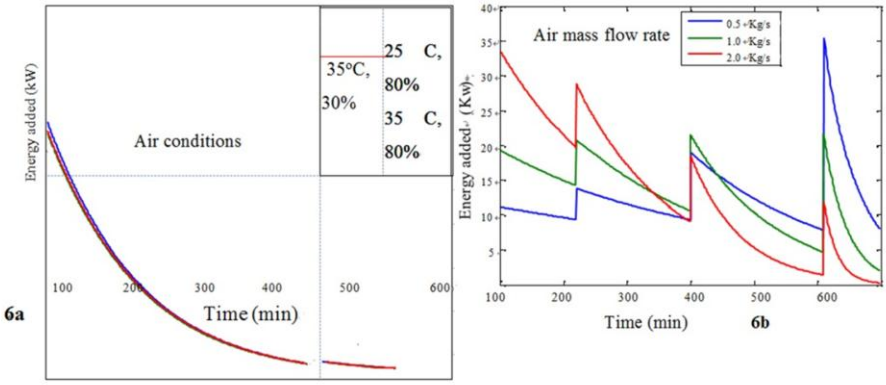


Figure 6 Effect of time on the energy requirement for the system (Abdulla et al., 2011).

a) Energy requirement for different conditions b) Energy requirement for different air flow rates.

Higher airflow not only increases the energy demand of the dryer but also the range in variation, which is due to the decline in evaporation as the fruit dries. Therefore, produces less change in the dryer’s humidity, the exhaust closes and less energy is lost from the system. This is in agreement with Turhan et al. (2013) in their study on evaluation of energy need for drying of sliced cornelian cherry fruits. They observed that drying air temperature and air flow had significant influence on the total energy requirement for drying (39.55kWh/kg).

Miller (1985) developed a model and a graphical approach to predict the energy requirement and drying time of fresh sliced fruits using humidity ratio difference (HRD) and airflow rates as the manipulated variables. The program required inputs were boxes/h, fruit/box, water/fruit, pre-dryer removal rate, and the surface water temperature, ambient conditions (dry and wet bulb, ^{o}C). Psychometric chart was used to determine the state points and establish the general recycle conditions. For the input data provided, the program estimated HRD level and the total energy required to maintain the specified state points.

The results reported an evident linear relationship between the total energy requirement and percentage air recycled. It also showed that the total energy requirement decreased linearly with increased percent air recycled which is an indication of the contribution of moisture load from the fruits (Figure 7). From this development, a fixed air recycling level, 50% to 60% could be established which would achieve a significant energy reduction with incorporating elaborate controls.

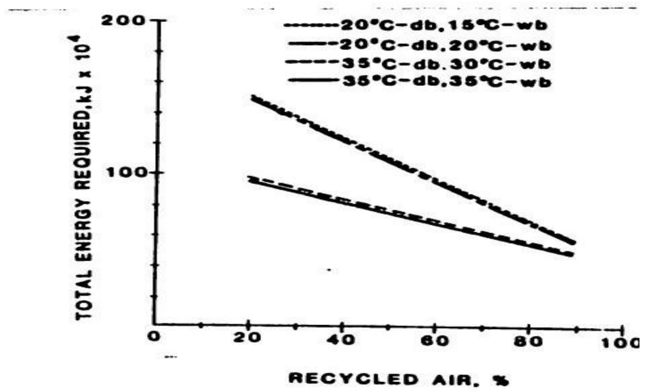


Figure 7 Relationship of drying potential and energy requirement for various air recycle percentages as reported by Miller (1985).

3. Conclusions and recommendations for future work

Drying energy requirement of sliced agricultural products has been estimated using different drying systems and approaches with a view to know the safest drying temperature and other drying conditions necessary for optimum drying and to reduce the energy cost in order to avoid over-drying and its associated waste. Crop variety, initial moisture content, drying air temperature, air velocity, crop specific heat capacity and slice thickness etc. have been identified as some of the major parameters affecting sliced crop drying energy requirement. Drying of sliced products has been found very advantageous in terms of uniform drying, low energy consumption and decreased drying time. The minimum actual energy requirement for drying sliced crops in convective hybrid solar and microwave dryers range from 5.21 – 90.4 MJ/kg of water removed and 4.22 - 24.99 MJ/kg respectively.

Computer models and graphical approach, as well as different empirical equations have been adopted by researchers for estimating the energy requirement of different sliced crops at specific drying parameters. The choice of correct drying temperature remains a central economic and ecological criterion in the drying of agricultural products, hence the need for drying energy prediction models for several sliced crops, having temperature as the key parameter.

From the review, microwave dryers are known for their high thermal efficiency, low energy consumption, and high quality dried product among other hot air convective dryers; but its cost implications vis-à-vis its electrical energy demand to generate the recommended power level (500W) for drying most sliced fruits and vegetables, result in higher energy requirement. Owing to this, hybrid solar drying systems with improved solar-air heater and heat recovery units have demonstrated superiority in terms of speed and quality of drying, and energy cost benefits. Models for predicting the amount of energy required to dry a given mass of different sliced agricultural products at different moisture contents using different drying systems should be developed since individual crop dryers can consume different combinations and quantities of energy per unit of water evaporated. A comparative study of different hybrid drying systems on the total energy consumption of different sliced crops should be carried out to select the best heat source combination and dryer type and/or design for a particular or range of crops with minimum gross energy demand. Experimental investigation of the influence of different sample geometries on specific energy consumption, drying rate and time is of great importance for future work.

However, in terms of varieties, sizes and stages of maturity, little or no studies have been carried out to estimate the energy requirement of different sliced roots and tubers, fruits and vegetables, using either hybrid hot air solar dryers or microwave dryers. Therefore, more studies to investigate the drying energy requirement for these products with these dryers are of considerable interest.

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