Energy consumption of agricultural dryers: an overview

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Abstract: Artificial dryers promote high-quality dried food products in spite of their considerable energy consumption. This paper presents a review of energy consumption of agricultural dryers in order to ensure optimal dryer design and cost effective dryer operation which yield better quality dried products. From the review, dryer design, type, crop characteristics, and ambient environmental conditions are seen as major factors affecting dryer energy consumption. Energy consumption of different dryers with different products was reported using different empirical expressions and graphical approaches. Results obtained show that microwave dryers have about 70% energy savings when compared to other artificial dryers due to their low energy consumption at higher power densities, but are cost-intensive when operated at the recommended 500 W power density for thin-layer or sliced products. For other types of dryers, energy consumption generally increases with increase in air velocity and drying time, and decreases with air temperature. It also decreases exponentially with drying time and moisture content for different sample geometries; while for microwave dryers, it varies inversely with temperature at constant air velocity. Vacuum-infrared dryer reveals that the total energy consumption varies inversely with the microwave power and slice thickness of crop sample and increases with increased absolute pressure. Other field test results for different drying systems and products were also presented. Suggestions were made towards improving reviewed dryers' efficiency in drying at optimal operating conditions.

Keywords: drying, dryer, agricultural products, heat, energy consumption

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1 Introduction

Many agricultural products have short supply period and must be preserved and stored for later use. Moisture removal is a typical preservation approach. Artificial drying is commonly used to remove moisture and thus improve the storability and quality of agro-food materials. By applying appropriate drying methods, product quality can be increased and losses reduced (Barbosa-Canovas and Vega-Mercado, 1996). In many developing countries like Nigeria, the direct use of the sun's energy for open-air drying is a common method, which is fraught with problems like poor dried product and reduced quality due to exposure to contamination from insect, flies, rodents, and dust; poor drying rate; long drying time; poor airflow and drying air temperature distribution *etc.* (El-Sebaii and Shalaby, 2012). These have led to traditional methods (hot air drying) being considered as an alternative for industrial dryers.

Dryer theory and technology have advanced greatly, which has led to the development of different drying systems with different energy efficiency and throughput. However, dryer energy consumption is important technical information necessary for optimal design and cost effective operation as well as proper meeting of the optimal storage conditions of agricultural products. Massive energy consumption in the drying industry has prompted extensive research regarding dryer energy consumption and product drying energy requirements, as well as concern for cost of drying agricultural products, its effects on the food supply chain, as well as its associated environmental effects such as increase in prevalent ambient temperature, increased greenhouse gas (GHG), air pollution, etc. (Koyuncu et al.,

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2005). Although drying is known for being energy intensive, in addition to the heat of vaporization of the moisture removed, energy goes into heating the solid material and into heating the drying medium used (Amos, 1998). Whether it comes as a part of a process or just as a preservation method for food and agricultural products, a relatively large amount of energy is required by the dryer to carry out this operation. The high cost is a direct consequence of the high latent heat of vaporization of water (2.26×10^6 J kg^{-1}) which most commonly is the water removed from the product during drying process (Raghavan, 2005). Although the specific heat capacity of the product is sufficiently lower than the latent heat of vaporization of water; the cost of energy provides a strong incentive to invent processes that will use energy efficiently.

Dryers are one of the most important equipment in food processing industries. Different types of dryers have been developed and used to dry agricultural products in order to improve their shelf-life. Most of these dryers irrespective of their configuration use an expensive source of energy such as electricity, geothermal, microwave power, infrared, liquefied petroleum gas, or a combination of solar energy, and other forms of energy. Convective air drying is the most common method of drying all kinds of agricultural products (Nwakuba, 2011). It could be in the form of active solar convective, microwave-convective, electrical-convective, heat pump, and hybrid convective dryers, which may be a combination of any of the four types. 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 consumption by the dryer. In order to circumvent this, Ohanwe and Sule (2007) posits that drying be done with sliced products or in thin layers 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, hence more convenient and cost effective.

In agricultural dryers, drying occurs by supplying heat to the wet material and thus vaporizing the liquid content. Generally, heat may be supplied by convection (direct dryers), conduction (contact or indirect dryers), and radiation or volumetrically by placing the wet product in a microwave or radio frequency electromagnetic field (Orsat et al., 2006). Most industrial dryers are of the convective type with hot air or direct combustion gases as drying medium. Almost all drying applications involve removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundaries of the drying product so that the heat may diffuse into the solid product primarily by conduction (Nwajinka, 2014). The liquid must travel to the boundary of the drying product before it is transported away by the carrier medium which in most cases is a gas (or by application of vacuum for non-convective dryers). Traditionally, a hot air dryer is made up of five basic components: the air heater, air mover, air duct system, chimney, and the cabinet holding the product. Nwakuba (2011) noted that apart from drying air properties and crop variables, energy consumption of agricultural product dryers is primarily dependent on the capacity and type of the air- heating and air-moving devices (assuming no heat loss to the walls and consequent low efficiency).

Selection of an efficient drying system is necessary in order to reduce energy consumption of a crop dryer during dehydration process and also minimize the quality degradation of dried products. The drying process should be in such a way that would apply minimum changes in products qualitative indexes. These indexes include physical aspects such as dimensions and size, texture, shape, wrinkles, and stiffness, as well as chemical changes such as browning reactions, discoloration, changes in vitamins, amino acids, and oxidation of substances (Okos et al., 1992). The objective of this paper therefore, is to review the energy consumption of different agricultural dryers for different agricultural products while developing a data bank of energy consumption requirements of drying systems for ease of selection of dryers. This work will also study the limitations and deficiencies in different drying systems and recommend improvements towards greater efficiency of the drying systems.

2 Dryer Performance Assessment

The many artificial dryers utilize the principle of hot air drying, where air is heated by the combustion of fossil fuels, electricity, and sun's energy, prior to being forced through the drying products. The heat sources can be singly or in combination for drying operation. These types of dryers however, require high energy inputs, due to their inefficiencies (Kemp, 2012). The thermal efficiency of a dryer is said to be the ratio of the minimum quantity of heat needed to dry a certain mass of feed to the heat actually used; that is, the theoretical energy required for moisture removal, which represents the minimum energy required to dry products is typically compared to the specific heat consumption (Billiris et al., 2011).

In order to assess dryer energy performance, its thermal efficiency (heat utilization factor) and specific energy consumption are considered by dividing the total energy supplied to the dryer by the mass of evaporated water (Raghavan et al., 2005; Tripathy and Kumar, 2009; Kemp, 2012; Motevali et al., 2012; and Hafezi et al., 2015). Energy consumption of a crop dryer is to large extent a function of dryer design/type and the ambient environmental conditions. Kemp (2012) states that crop dryers consume significantly more energy through its heat supply units than the latent heat of evaporation. This energy consumption can be reduced through heat recovery. The simplest form of heat recovery according to Singh and Heldman (1999) is exhaust air recirculation. The study suggested that when the available space for ductwork and the distance between the input and the exhaust is not too great, a portion of the exhaust air can be routed back to the input of the heat source, which preheats the inlet air and thus reduces the dryer energy consumption at that point.

However, individual crop dryers could consume varying quantities of energy per unit mass of water evaporated irrespective of the heat source or the number of heat sources: single or hybrid. It is therefore, useful to consider energy consumption for the general case. Therefore, all the possible elements of energy consumption and supply in agricultural products drying that appear in various combinations in specific drying systems can be listed as follow (Kemp, 2012):

i. Latent heat required evaporating water from a product, which is directly and invariably determined by the crop volume, specific gravity, and expected percentage moisture change (expressed in dry basis).

ii. Heat loss from dryer structures by conduction from high-temperature interior through the walls, ceiling, and floor to lower temperature regions outside.

iii. Heat loss associated with vent air used to remove water from the dryer (and air loss from leaky dryer structures in excess of necessary venting) and/or chimneys.

iv. Sensible heat required to heat the product and drying chamber to drying temperature. Electrical energy needed for air movement: In agricultural product dryers, the actual energy demand for air circulation varies with air velocity, package width, and nature of the material being dried.

3 Evaluation of Dryer Energy Consumption

According to Billiris et al. (2011), the first step in quantifying the performance of a drying process is to calculate the theoretical energy required by the system to remove water from the matrix of the food material. In their work, they developed three models (see Table 1) that predict the amount of energy (Q_t) required by a crop dryer to dry a unit mass of different types of rice in thin-layers with specific moisture contents at a particular temperature. The models were developed using a semi-theoretical approach, where isotherms desorption were applied in conjunction with the Clausius-Clapeyron equation. The entire amount of energy, Q_T required to remove water from the product (i.e. total heat of desorption), moisture content and temperature data were used to statistically determine the constants of the relationships in the equations. The mathematical expressions that predict the energy requirement at a given drying temperature were developed using appropriate values of the constants as expressed in Equation (1).

$$Q_T = A_1\left(MC_f - MC_1\right) + B_1.T\left(MC_f - MC_i\right) + \frac{(A_2+B_2,T)}{-A_3}.e^{-A_3.MC_f} - e^{-A_3.MC_i} \quad (1)$$

Where: Q_T = energy requirement to dry rice from initial moisture content to the desired moisture content (kJ kg^{-1} water); A_1, A_2, A_3, B_1 and B_2 are constants of the equation estimated iteratively by fitting the non-linear model; MC_i and MC_f = initial and desired moisture contents, % db.; T = temperature, °K. They (Billiris et al., 2011) suggested that in order to obtain accurate dryer theoretical energy requirements, it is necessary to include the moisture contents, temperature and the constant terms in the above equation, because as moisture content decreases, the contribution of the exponential term becomes more important as illustrated in Table 1.

Table 1 Equations developed based on Equation (1) to predict the dryer energy (Q_{Trice}) required to dry rice

Rice type	Equation	Temp. range, °C.
Medium-grain/non-parboiled	$Q_{Trice} = (3,150,878 - 2377T)(MC_f - MC_i) + [e^{-23.2MC_f} - e^{-23.2MC_i}]\frac{(12,725,771 - 96011T)}{-23.2}$	10-60
Long-grain/non-parboiled	$Q_{Trice} = (3,189,745 - 2496T)(MC_f - MC_i) + [e^{-24.2MC_f} - e^{-24.2MC_i}]\frac{(9,742,417)}{-24.2}$	10-90
Long-grain/parboiled	$Q_{Trice} = (3,151,394 - 2377T)(MC_f - MC_i) + [e^{-23.0MC_f} - e^{-23.0MC_i}]\frac{(8,107,920 - 6117T)}{-23.0}$	10-60

Source: Billiris et al. (2011).

Results obtained indicated that the energy required to dry rice grains from an initial moisture content, MC_i to a desired moisture content, MC_f of 12.5%, 13%, and 14.5% on a per unit mass of water removed at 60 °C decreased exponentially as MC_i increases, when expressed on per unit mass of water removed as shown in Figure 1. In other words, Q_{Trice} increases as MC_f decreases: more energy is required to reach lower MC_f as a result of increase in the intra-particle resistance to moisture migration at lower MC_f.

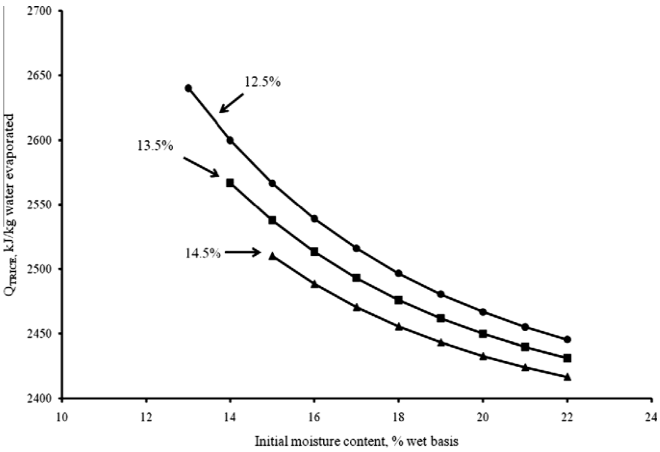


Figure 1 Total energy required to dry rice (Q_T) to 12.5%, 13.5%, and 14.5% (wb) moisture content of the long-grain, non-parboiled rice at 60 °C. (Billiris et al., 2011)

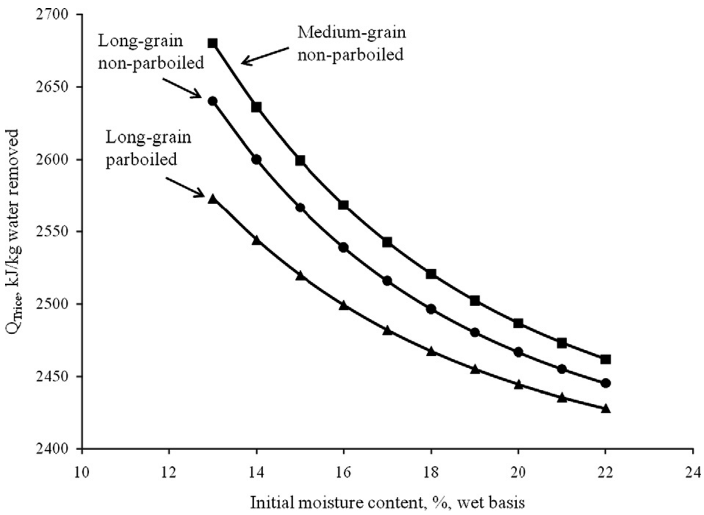


Figure 2 Energy required to dry rice (Q_{Trice}) to 12.5% (wb) moisture content for long-grain non-parboiled, long-grain parboiled and medium-grain non-parboiled rice at 60 °C. (Billiris et al., 2011)

Figure 2 illustrates that the dryer energy required to dry rice from MC_i to MC_f (Q_{Trice}) decreases exponentially as MC_i increases for the three rice cultivars. This is because the amount of energy required to dry a unit mass of the grain sample varies inversely with binding force between the internal water and the grain kernel which increases as the drying process progresses. More energy is required by the dryer to dry the non-parboiled rice than the parboiled rice. This behavior is believed to have been as a result of high resistance of the intra-particle resistance to moisture diffusion in the non-parboiled rice. The long-grain parboiled has lower strength of water-solid bonds in its kernel than the medium grain and long-grain non-parboiled rice varieties.

Ajiboshin et al. (2011) conducted a study to evaluate the energy requirement of a cassava flour dryer and the cost of drying five tons of five unknown different varieties of cassava flour per day using a diesel fired flash dryer on the assumption that the final moisture content is 10%.The values of moisture content in the fresh cassava varieties M_{fc}, granulated wet cake M_{gc}, and moisture content loss to drying operation M_{lp} are shown in Table 2.

Table 2 Evaluation of daily drying energy requirement

Variety	M_{lk}, kg	Daily energy, E_{TR} GJ	Amount, ₦
V_1	5,742.50	14.79	57,517.00
V_2	6,047.50	15.57	60,550.00
V_3	6,257.50	16.11	62,650.00
V_4	6,675.00	17.20	66,889.00
V_5	6,750.00	17.40	67,667.00

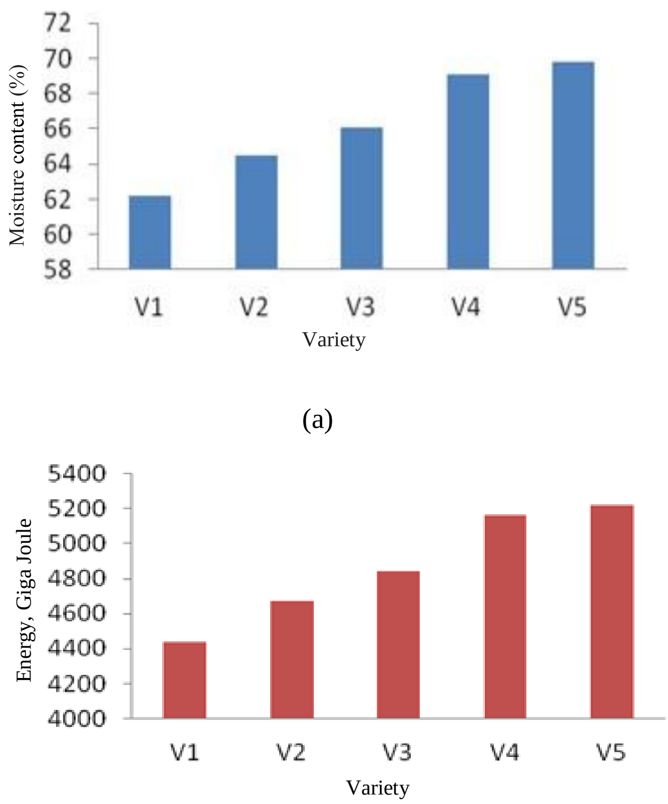
Source: Ajiboshin et al. (2011).

The estimated total energy requirement per annum for drying, E_{TR} was expressed as Equation (2).

$$E_{TR} = M_{lk}[L_V + C_W(100 - t_r)] \quad (2)$$

Where: M_{lk} = moisture loss to drying operation, Kg; L_v = latent heat of vaporization of water = 2.26×10^6J kg^{-1}; C_w = specific heat capacity of water = 4,200J kg^{-1} °K; t_r = room temperature, °K.

From the result obtained, varieties V_1 and V_5 had the least and highest daily moisture losses to drying operation respectively. This is may be attributed to their characteristic microcellular arrangement vis-à-vis the water-solid bonds of the variety. The intra-particle resistance to moisture migration in the cassava matrix increases with the variety. This results in the increase in the values of moisture loss (M_{lk}) and the dryer total energy requirement (E_{TR}) of cassava variety (from V_1 to V_5). The E_{TR} and cost of drying for all the varieties also followed the same trend as M_{lk}. Figure 3a and 3b illustrate that the higher the moisture content level, the higher the dryer energy requirement.



(a)

(b)

(a) Moisture content of varieties

(b) Energy requirement of different cassava varieties.

Figure 3 Moisture level of different cassava varieties and dryer energy consumption (Ajiboshin et al., 2011)

This shows that moisture content plays an important role in determining the energy required for the drying operation. It is also evident that the faster the moisture removal from the varieties to the appropriate storage moisture level (10%), the more efficient the dryer may said to be vis-á-vis its specific energy consumption.

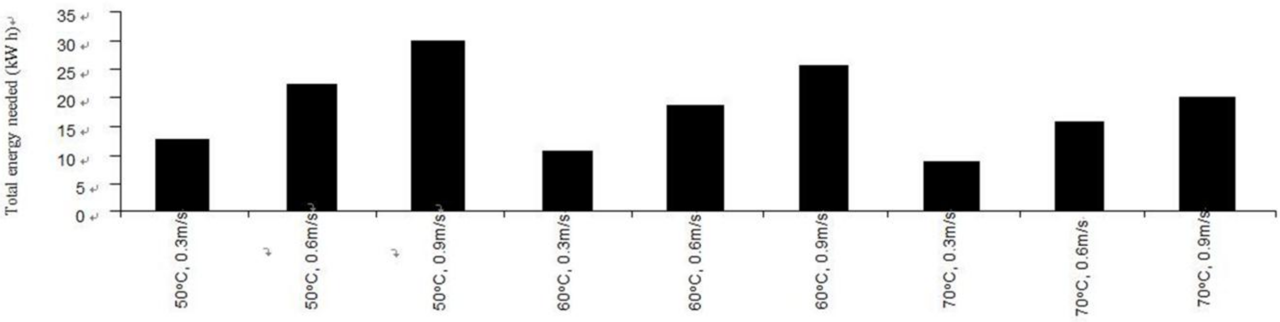
Specific energy consumption (SEC) is referred to as the heat required eliminating one kg of water (moisture) from a wet agricultural product during heated-air drying. Koyuncu et al. (2005) carried out an experimental study on a convective parallel airflow dryer using cornelian cherry fruits (*Cornus mas L.*).The dryer total energy consumption and specific energy consumption were estimated using Equations (3) and (4) respectively, which amount to the heat energy given to drying air by the electric heater.

$$E_t = A\upsilon\rho_a C_{pda}\Delta T t \quad (3)$$

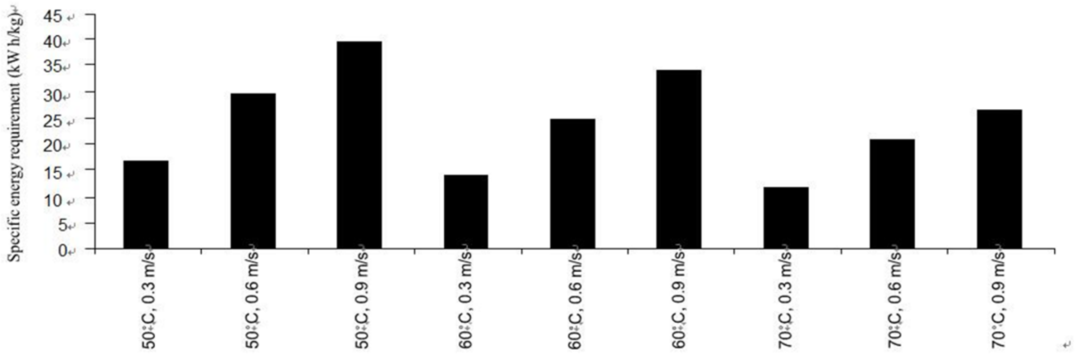
$$E_{kg} = \frac{E_t}{W_0} \quad (4)$$

Where: E_t = dryer total required energy in each drying phase (kWh), A, is the sample plate area (m^2), υ = air velocity (m s^{-1}), ρ_a = air density (kg m^{-3}), t = total drying time of each sample (h), ΔT = temperature difference between ambient and hot air (°C), and C_{pda} = specific heat of air (kJ kg^{-1} $°C^{-1}$); E_{kg} = specific energy consumption (kWh kg^{-1}), W_o = sample weight (kg).

Drying air was heated by the electric heater. In order to produce different temperatures and air velocities, the electric current of the heater and the rotation of the fan were adjusted manually. To measure the energy consumption, air velocity and drying air temperatures at different points, a Wattmeter, air flow meter and thermocouple were connected to the dryer respectively. Results obtained are shown in Figures 4a and 4b to illustrate the total energy consumption of the dryer and energy required by the dryer to dry 1 kg of the cornelian cherry fruit.



(a)



(b)

(a) Total energy requirement of the dryer at different temperatures and drying air velocities

(b) Energy requirement for drying 1 kg of product at different temperatures and drying air velocities.

Figure 4 Energy consumption of a convective parallel airflow dryer (Koyuncu et al., 2005)

There is strict correlation between the two figures. This is because of the fact that the values of Figure 4b were obtained from the value of Figure 4a by calculation. As seen from these figures, the minimum specific energy consumption of 11.57 kWh kg^{-1} is needed to dry one kg of cherry fruits at a temperature of 70°C and air velocity of 0.3m s^{-1}. The maximum specific energy consumption of 39.55 kWh kg^{-1} is needed at 50°C and 0.9m s^{-1}. The energy consumption is decreasing with increasing drying temperature, and air velocity is more effective on energy consumption, in that more energy is consumed for higher rotation of the air-moving device. This is so because the drying air does a lot of work to overcome the mass diffusion of internal water and consequent surface evaporation (Nwakuba et al., 2016). In other words, energy consumption varies inversely with temperature, at constant air velocity. These situations can be explained by the total drying time decreasing with rising drying air temperature, and low air velocity reduces the air flow. It is clearly seen from Equation (3) above that low drying time and low air flow lessen energy consumption. This corroborated with the experimental observations of Motevali et al. (2012) in dryer specific energy consumption of Jujube plant dehydration at different temperature levels and air velocities. During their test, the dryer energy consumption and energy requirement were calculated using Equations (3) and (4) above. A prediction equation was developed, involving the specific energy consumption, dryer temperature, and air velocity from a multiple regression analysis (with 0.95 R^2-value) as expressed in Equation (5).

$$E = -0.444 + 1.05T + 126.33V - 0.01833T^2 - 23.333V^2 - 1.2TV \quad (5)$$

Where: E = specific energy requirement (kWh kg^{-1} water), T = dryer temperature (°C), V = air velocity (m s^{-1}).

3.1 Energy consumption of different dryers

Some works have been done on estimation of the energy consumption of some common dryer types such as: microwave dryers, vacuum pump infra-red dryers, solar dryers, and hybrid dryers. These dryers consume varying quantities of energy depending on the type of crop to be dried and the desired final moisture level.

3.1.1 Microwave dryers

In microwave drying, the quick absorption of microwave energy by crop sample is dependent upon the moisture content of the material, which results in rapid evaporation of internal water and offers significant energy savings, as well as good quality product (Orsat et al., 2006; Zarein et al., 2013, and Motevali et al., 2014). Darvishi (2012) estimated that the specific energy consumption for drying of potato slices using a microwave dryer ranges between 4.22MJ kg^{-1} H_2O and 10.56 MJ kg^{-1} H_2O for minimum and maximum power densities of 5 and 15W g^{-1} respectively, with major parameters as slice thickness, microwave power densities and moisture ratios as function of drying time. Darvishi et al. (2013), in a related study, investigated the effects of microwave drying technique on energy consumption, drying efficiency and characteristics of potato slices with initial and final moisture contents of 75% (wb) and 4% (wb) respectively under the power densities of 200, 250, 300, 350, 400, 450, and 500 W. Results obtained show that the high moisture content during the first phase of drying resulted in higher energy consumption in the form of microwave power, and higher drying rates which in turn yielded very high energy efficiency due to the higher moisture diffusion. Consequently, as the drying progressed, loss of moisture in the product resulted in a decrease in the energy consumption (power absorption) of the microwave dryer.

Similarly, Zarein et al. (2013) worked on the energy consumption and thin-layer drying of carrot slices under four microwave power densities: 100, 300, 500 and 700 W and slice thickness of 7 mm. Results obtained showed that the microwave power significantly affected the drying time, drying rate, effective moisture diffusivity and specific energy consumption. The value ranged from 10.27 to 23.29 kWhr kg^{-1} of optimized specific energy consumption. The lowest specific energy (27 kWhr kg^{-1}) was obtained at 300 W microwave power level. From Figure 5, the highest energy is consumed at 100 W power reduced drastically at the 200 W power and slightly increased again at 500 and 700 W power. This is as a result of the high initial amount of moisture required to be heated up to the evaporation temperature for mass diffusion which requires high amount of energy.

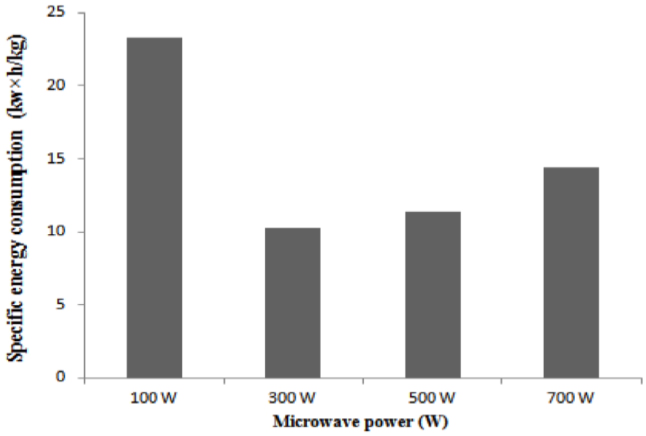


Figure 5 Specific energy consumption for microwave drying of carrot slices as reported by Zarein et al (2013).

Similar trends were observed in the works of Zarein et al. (2015) for sliced apple, Soysal et al.(2006) for parsley (5.10 to 4.18 MJ kg^{-1} water), and Raghavan et al. (2005) for grape, and mango (81.2 and 90 MJ kg^{-1}).The specific energy consumption was estimated using Equation (6).

$$Q = \frac{60P\Delta t}{M_W} \times 10^{-6} \quad (6)$$

Where: Q = specific energy consumption (kJ kg^{-1} water removed), P = microwave power (W), Δt = time interval (seconds), and M_W = mass of water removed (kg).

Generally, the specific energy consumption of microwave dryers was observed to have about 70% energy savings as compared to other convective drying processes (Sadi and Meziane, 2015).

3.1.2 Vacuum infrared dryers

Infrared radiation is a form of electromagnetic radiation absorption of which causes heat vibration in food stuff and agricultural produce. It is one of the best methods for thin layer drying of agricultural materials (Swasdisevi et al., 2007; Motevali et al., 2015). Drying under vacuum is generally performed since under vacuum, water evaporates at low temperature; hence, drying can be performed at low temperature. This type of dryer has recently received much attention as an alternative drying technique due to the minimal energy loss during the process. They are characterized with production of high quality products, high energy efficiency; high heat transfer rate sand reduced drying time. When infrared radiation is used to heat or dry moist material, the energy of radiation penetrates through the material and converts into heat (Ratti and Mujumdar, 1992; Swasdisevi et al., 2007). Since the material is heated rapidly and more uniformly and since infrared radiation energy is transferred from the heating element to the product without heating the surrounding air, the energy consumption in infrared dryers is relatively low compared to hot air drying. Nowadays, infrared radiation is applied to several dryers because it has advantages of increased drying efficiency and space saving (Rattiand Mujumdar, 1995; Yamazaki et al., 1992).

The energy consumption trend of microwave dryers is however, contrary to the experimental observations of the result of Hafezi et al. (2015) with a vacuum-infrared dryer. Their study reveals that dryer the total energy consumption varies inversely with the microwave power and slice thickness of crop sample and increases with increased absolute pressure. The dryer energy consumption was calculated from the electric energy consumed by the operation of the vacuum pump and infrared lamp expressed in Equations (7) and (8). The total dryer energy consumption E_t, is the summation of Equations (7) and (8).

$$E_1 = \int_{t=1}^{T} V.I.\Delta t.cos\Phi \quad (7)$$

$$E_2 = \int_{t=1}^{T} V_l.I.\Delta t \quad (8)$$

Where: E_1 and E_2= power consumed by the pump and infrared lamp (kWh) respectively, V and V_l= nominal pump voltage and lamp voltage (V) respectively, I = pump and lamp electric current intensity, T = drying time (hr.), Φ = electric power factor.

3.1.3 Solar dryers

Solar drying of agricultural products is known for its non-energy intensive process, especially the open sun drying due to its low thermal efficiency (Nwakuba, 2011; Hii et al., 2012). Solar dryers can save more energy compared to other industrial dryers since they use the available solar energy. Moreover, lower drying times and costs, space-efficiency, higher product quality, environmental-friendliness, less CO_2 emission, and higher efficiency are among their advantages (Punlek, 2009; El-Sebaii and Shalaby, 2012; Vijaya and Iniyan, 2012).Various investigations have been conducted to study their specific energy consumption using different drying crop samples such as: carrots slices, agar gel and Gelidium seaweeds, garlic cloves, pistachios, food and non-food (Holtz et al., 2010),banana slices (Mousa and Farid, 2002; Swasdisevi, 2009).

Sharma and Prasad (2004) evaluated the specific energy requirements of three different types of solar dryers: solar cabinet dryer (SCD), forced air dryer (FAD), and hybrid active dryer (HAD) in drying gutted fish samples from 87% wb to 6% wb moisture content using Equation (9):

$$H = \left(\frac{Total\ energy\ supplied\ in\ drying\ process}{amount\ of\ water\ removal\ during\ drying}\right) = \frac{E_T}{M_W} = \frac{(h_1+h_2+h_3)}{M_W} \quad (9)$$

Where: H = specific energy consumption (kJ kg^{-1}), h, h_2, and h_3 = heat supplied to the drying air for each dryer type respectively (kJ); M_W = amount of water removed (kg); E_T = total energy supplied (kJ).

Results obtained show that large amount of energy is consumed in drying the gutted prawn fish samples due to biological characteristics of the fish samples, initial and desired moisture contents, dryer configuration, and capacity of heat source and air-moving devices of each of the dryer types. However, there was no significant difference in specific energy consumption during drying in any of the three dryers. This indicates that the energy consumption for drying of fish using solar dryer is relatively high when compared to sliced crops which lies within the range of 12-60.85 kWh (Nwakuba, 2011; Hii *et al.*, 2012; and Lopez-Vidana et al., 2013). This can be considerably reduced through the use heat recovery systems and brining of the gutted fish sample prior to drying.

Yahya et al. (2011) conducted an experimental study to evaluate the energy requirement of a green herbal tea hybrid solar-assisted dryer. The dryer consisted of a V-groove collector; two axial fans and an auxiliary heater. Measurements of temperatures, relative humidity, moisture contents, air velocities, solar radiation on the collector surface, and sample mass were recorded during the tests. Figure 6 shows the variations of energy consumption for the drying process with time.

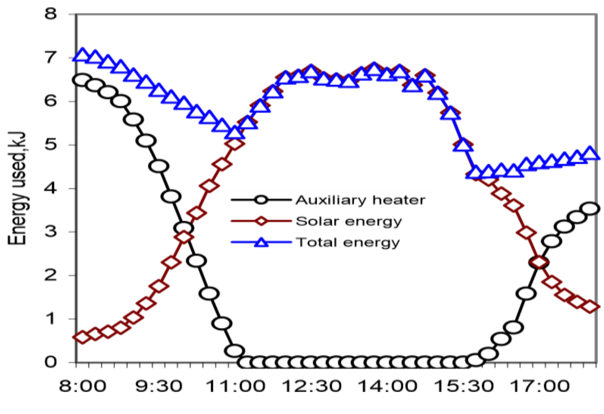


Figure 6 Variations of dryer energy consumption with time (Yahya et al., 2011)

The dryer consumed a maximum energy of 65 kJ, 68.7 kJ, and 70 kJ from the electric heater, solar collector, and hybrid source respectively calculated using Equation (10).

$$Q_T = Q_U + Q_{HE} = G_a C_{pa}(T_{Cout} - T_{Cin}) + G_a C_{pa}(T_{HTout} - T_{HTin}) \quad (10)$$

Where: Q_u and Q_{HE} are useful energy of collector and electric auxiliary heater respectively; T_{Cin} = collector inlet temperature, °C; T_{Cout}= collector outlet temperature, °C; G_a = mass flow rate of product, Kg s^{-1}; C_{pa} = specific heat capacity of product at constant pressure, J kg^{-1} K^{-1}; T_{HTout} and $T_{HT\ in}$ = auxiliary heater outlet and inlet air temperatures respectively, °K. The methodology employed was similar to that of Hyong et al. (2007).

A similar result was obtained by Sarsavadia (2007) when drying onion slices from 86% to 7% moisture content wet basis with a flat plate solar-assisted dryer. Also Tripathy and Kumar (2009) observed that dryer specific energy consumption for different sample geometries decreases exponentially with the drying time and moisture content. As drying progresses, the moisture content of food product decreases, resulting in reduction of energy requirement. They attributed higher values of specific energy consumption obtained in the slice sample geometry to faster moisture evaporation rate which decreases rapidly as the product surface becomes completely dry; while lower dryer specific energy consumption is because of rapid mass evaporation in cylinder-shaped samples due to higher surface heating effects resulting from more exposed area per unit mass.

3.1.4 Hybrid dryers

Experimental study on energy consumption of a hybrid convective electric-gas dryer for drying of onion slices was done by El-Mesery and Mwithiga (2012). The energy consumed by the electrical dryer through the heating element was determined using a digital electric counter. While that of the energy consumption of the gas dryer was determined by weighing the gas cylinder using a weighing balance. The difference in mass of the gas bottle before and after drying process was measured and converted into consumed energy (Q_G) by the use of Equation (11).

$$Q_G = M_G H \qquad (11)$$

Where: MG = mass of consumed butane gas (kg), H = lower heating value of butane gas (45600 kJ kg-1).

The energy released on combustion of the gas and the energy measured electrically can be related to energy actually used to evaporate the water in what is commonly referred to as specific energy consumption (SEC) as expressed in Equation (12):

$$SEC = \frac{total\, electrical\, or\, gas\, energy}{mass\, of\, water\, removed} \qquad (12)$$

SEC for both the electric and gas heat sources of the dryer, different air temperatures and air velocities are presented in Figure 7. From the figure, SEC decreases with increase in air temperature but increases with increase in air velocity in both dryer heat sources. In the electric source, when the temperature of drying air was increased from 50 °C to 70 °C while holding the air velocity constant at 0.5 m s^{-1}, the specific energy consumption decreased from 65.45 to 43.34 MJ kg^{-1} of water evaporated. At the fixed air velocity of 2 m $s^{-1}$and for the same air temperature range of 50 °C to 70 °C, the specific energy consumption of the electrical dryer decreased from 84.64 to 70.59 MJ kg^{-1} of water evaporated.

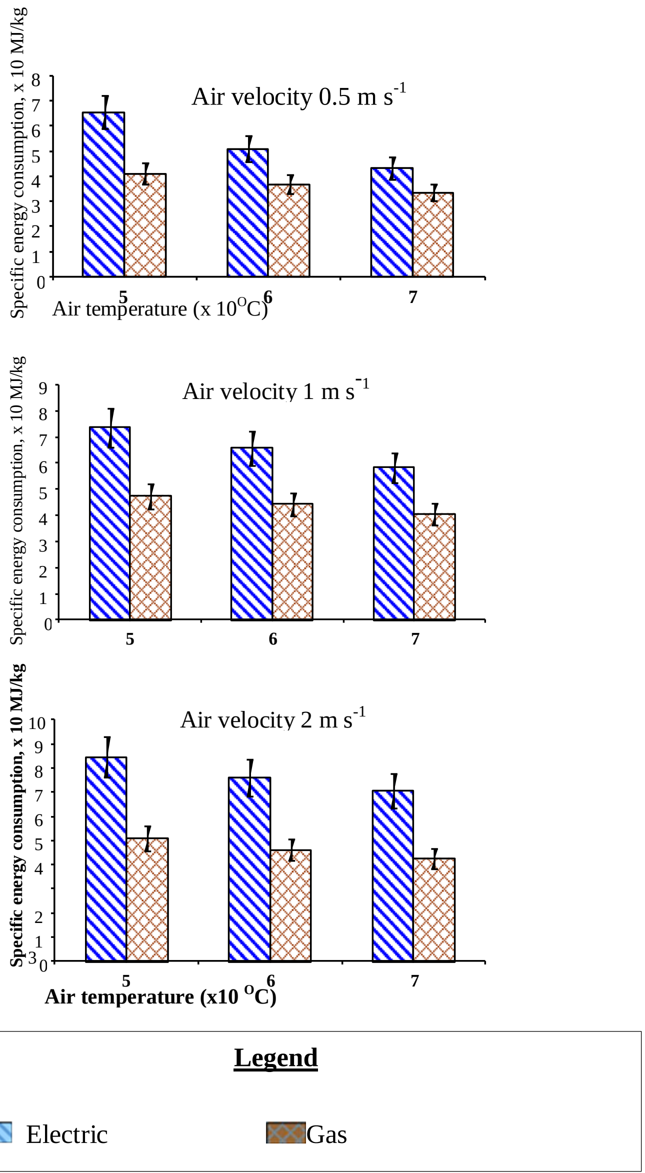


Figure 7 Specific energy consumption at different levels of drying air temperature and air velocity for both the electrical and the gas dryer as reported by El-Mesery and Mwithiga (2012)

These figures illustrate that less energy is wasted when the temperature is high and air velocity is low. In other words, increasing air temperature causes decrease in SEC values. Also, increasing air velocity causes an increase in SEC. The implication is that using high air temperature and drying conditions result in a sharp increase in the dryer energy consumption. Accordingly, low temperature level with high air velocity causes a relative decrease in moisture diffusivity, resulting in higher SEC values. The SEC values also compare to the value of 64 MJ kg^{-1} determined by Jindarat et al. (2011) for hot air drying at 70°C. Sharma and Prasad (2006) found values that ranged from 140 to 215 MJ kg^{-1} while drying garlic and their values showed a decreasing trend with increase in temperature within the range of 40°C to 70°C, although the SEC values are higher than that of the electric dryer. For the gas dryer, increasing the drying air temperature from 50°C to 70°C at a fixed air velocity of 0.5 m s^{-1} caused the dryer specific energy consumption to decrease from 41.22 to 33.56 MJ kg^{-1} of evaporated water. At a fixed velocity of 2 m s^{-1}, the specific energy consumption in the gas dryer decreased from 50.89 to 42.52 MJ kg^{-1} of water evaporated, when the air temperature was increased from 50°C to 70°C. Similar trends were reported by Khoshtaghaza et al. (2007), Aghbashlo et al. (2008) and Chayjan et al. (2010) in estimating the specific energy of consumption for drying grape and berberis fruits in a convective hot air dryer in the range of 547 and 1904 MJ kg^{-1}. They observed that increase in drying temperature caused a decrease in the specific energy consumption. The effect of air velocity on increasing specific energy value was more than the air temperature. Results obtained indicated that increasing the drying temperature in each air velocity level affects the energy consumption inversely. In other words, increasing the air temperature shortens the drying time, thus the energy consumption is reduced. Also decreasing the air velocity, effective contact between air and fruit was increased and the specific energy consumption decreased.

In general, the SEC of the gas dryer was observed to be lower than that of the electric dryer at all conditions of air temperature and air flow settings. This is probably because of the longer on/off periods of the electrical heater elements when compared to the gas burner and the fact that the electric heaters still retained a high thermal mass even when stitched off.

4 Conclusions

Drying fresh agricultural produce with heated-air dryers requires a relatively large amount of energy. This energy consumed by dryers has been evaluated for different artificial dryers with different products in order to obtain optimal dryer design, cost effective operation as well as optimal storage conditions of harvested agro products. Dryer energy consumption is a function of material properties such as sample geometry and thickness, initial and final moisture contents; specific heat of product, dryer type and configuration, operating parameters like air velocity, temperature, power density, absolute pressure, crop energy requirement, drying time, etc. Selection of efficient drying system is paramount in order to reduce the energy consumption of a crop dryer that would yield a minimal effect on the qualitative indexes of the product. In assessing dryer energy performance, its thermal efficiency and specific heat consumption are considered by dividing the total energy supplied by mass of evaporated water. Its actual energy consumption is estimated by considering the ratio of thermal efficiency and energy consumption. This energy consumption can be reduced through heat recovery of exhaust air.

It has been established from the review that energy consumption of microwave dryers have about 70% energy savings as compared to other convective dryers due to their low energy consumption at higher power densities, but the cost of running microwave dryers at the recommended power level of about 500 W for thin-layers drying mars its usage as it results in higher energy requirement in the form of microwave power density. Energy consumption varies with dryer type, drying conditions, and type of product to be dried. For hot-air dyers, it increases with increase in air velocity and drying time, and decreases with temperature. It also decreases exponentially with drying time and moisture content for different sample geometries; while for microwave dryers, it varies inversely with temperature at constant air velocity. Vacuum-infrared dryer reveals that the total energy consumption varies inversely with the microwave power and slice thickness of crop samples and increases with increased absolute pressure.

Given the outputs of the dryers highlighted in the review, it implies that future dryers are more likely to be energy intensive which would impact negatively on the food supply chain as a result of increased cost of drying due to high energy consumption rate, as well as its associated environmental effects such as increase in prevalent ambient temperature, increased greenhouse gas (GHG), air pollution, etc. It is very paramount to recommend recirculation of drying air through heat recovery units and improved air heaters (with low power capacity and resistivity) suitable for considerable reduction in dryer energy consumption. However, a comparative study be considered for different hybrid dryers with and without heat recovery units on energy consumption for different products with different geometries at different initial and final moisture levels. There is need to develop computer prediction models for total energy prediction of the above discussed dryer types and others for different crops at varying drying conditions. Further works on investigation of the correlation between energy consumption and dryer characteristics such as contact area between air and drying product, dryer dimension, and airflow for selected fresh produce is recommended. Since it has been established from available literature that little or no studies have been carried out to estimate the energy consumption of different cultivars of cereals at different temperature levels and moisture content; root and tuber crops, fruits and vegetables of various varieties, sizes, slice thickness and stages of maturity using either any of the convective hot-air dryers in single or hybrid form, or the microwave dryers. Therefore, more studies to investigate energy consumption for these products by these dryers are of considerable interest.

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