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HEAT PUMP DRYING OF FRUITS AND VEGETABLES: PRINCIPLES AND POTENTIAL FOR SUB SAHARA AFRICA

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ABSTACT: Heat pump technology has been used for heating, ventilation and air-conditioning in domestic and industrial sectors in most developed countries of the world including South Africa. However, heat pump drying (HPD) of fruits and vegetables has been largely unexploited in South Africa. Although studies on heat pump drying started in South Africa several years ago, not much progress has been recorded to date. Many potential users view heat pump drying technology as fragile, slow and high capital intensive when compared with conventional dryer. This paper tried to divulge the principles and potentials of heat pump drying technology and the conditions for its optimum use. Also, various methods of quantifying performances during heat pump drying as well as the quality of the dried products are highlighted. Finally, some erroneous views on the heat pump drying process were clarified.
Keywords: Heat pump drying (HPD), energy efficiency, cost of operation, performance indicators, quality

1. INTRODUCTION

Consumers, in a bid to have healthier and more natural foodstuffs, have been encouraged to increase their daily intake of fruits and vegetables since their nutritional value as suppliers of vitamins, minerals, fiber and low fat is recognized. However, the water content of most of fruits and vegetables is higher than 80%, which limits their shelf-life and makes them more susceptible to storage and transport problems. Vegetables and fruits can be made more acceptable to consumers by drying (Abonyi et al., 2002) There is also a big market for dehydrated fruits and vegetables which increases the importance of drying for most of the countries worldwide (Funebo & Ohlsson 1998). In Sub Sahara Africa, a lot of losses of fruit and vegetables are usually experienced during the peak seasons and only a few cold storage of fruits and vegetables is being practiced. However, Bonazzi and Dumoulin (2011) enumerated the reasons for drying as follows:

» To extend the shelf life of foods without the need for refrigerated storage;
» Reduce weight and bulk volumes, for saving in the cost of transportation and Storage;
» To convert perishable products (surplus) to stable forms (e.g., milk powder);
» To produce ingredients and additives for industrial transformation (so-called intermediate food products (IFPs), like vegetables for soups, onions for cooked meats, fruits for cakes, binding agents, aroma, food coloring agents, gel-forming and emulsifying proteins, etc.),
» To obtain particular convenience foods (potato flakes, instant drinks, breakfast cereals, dried fruits for use as snacks, etc.), with rapid reconstitution characteristics and good sensorial qualities, for special use, such as in vending machines, or directly for consumers.

Furthermore, loss of product moisture content during drying results in an increasing concentration of nutrients in the remaining mass making proteins, fats and carbohydrates to be present in larger amounts per unit weight in the dried food than in the fresh. Therefore, drying is a very indispensable operation. In the process of drying, heat is required to evaporate moisture from the product and a flow of air to carry away the evaporated moisture, making drying a high energy consuming operation (FAO, 1994) and there are different heat sources available for drying (Jangam & Mujumdar, 2010). However, due to the increasing prices of fossils and electricity, the emission of CO_2 in conventional drying methods, green energy saving and other heat recovery methods for processing and drying of produce becomes very important. This paper tried to divulge the principles and potentials of heat pump drying technology and the conditions for its optimum use. The article attempted to bring together the basic information on the effects of heat pump drying which are inconveniently scattered among several journals and texts to justify the need to carry out cutting-edge research on heat pump drying in Sub Sahara Africa.

2.CASE FOR HEAT PUMP DRYING APPLICATION IN SUB SAHARA AFRICA

Despite the fact that energy failure is a common experience in most Sub Sahara Africa, the use of air conditioning and refrigeration has been on the increase both in the industries as well as in domestic uses because of the prevalent hot conditions of climate in the region. Harnessing of the recoverable heat from these processes which otherwise would have been wasted to some useful purpose would be a worthwhile exercise. Also, drying to produce high quality agricultural produce is yet a bottleneck in most Sub Sahara countries, especially Nigeria. Up till now a lot of food losses are being experienced due to inadequate storage and processing techniques. For development of sustainable energy, three important technological changes have been required: energy economies on the demand side, efficiency improvements in the energy production and renewing of fossil fuels by various sources of renewable energy. In this regard, HPD systems improve energy efficiency and because less fossil fuel consumption. Since heat pump drying is a low temperature drying process, it will give a double advantage over the conventional, common and unreliable sun drying in the region.

3. CONVENTIONAL AND HEAT PUMP DRYING PROCESSES COMPARED

Heat pump drying has the ability to recover the latent and sensible heat by condensing moisture from the drying air (Jangam & Mujumdar, 2010). The recovered heat is recycled back to the dryer through heating of the dehumidified drying air hence the energy efficiency is increased substantially as a result of heat recovery which otherwise is lost to the atmosphere in conventional dryers (Current Concerns 2009). This enables drying at lower temperatures, lower cost and operation even under humid ambient conditions. Many articles have been written on the different types of heat pump dryers available (Mujumdar & Jangam, 2011). Also, the comparative efficiencies and advantages of heat pump dryers over vacuum and hot-air dryers are shown in Table 1. One improvement that heat pump has over other heat sources for drying is that it can be applied to any kind of dryer. Any dryer that uses convection as the primary mode of heat input can be fitted with a suitably designed heat pump but dryers that require large amounts of drying air e.g. flash or spray dryers are not suited for HP operation (Jangam & Mujumdar, 2010).

A heat pump is attractive because it can deliver more energy as heat than the electrical energy it consumes. Also it can use modified atmospheres to dry sensitive materials like fruits and vegetables. The clean water which is gained by condensation might even be used as a side product and the heat pump can also be used as cooling plants, which is a basis for further developments towards the cooling and storing of fruit (Current Concerns 2009). 'The capacity of air to remove moisture depends on its initial temperature and humidity' (FAO 1994). The changes in air conditions when air is heated and passed through a bed of moist product are shown in Figure 1.

Table 1: Comparison of HPD with other commonly used dryers. Source: Mujumdar and Jangam [5]

Item	HPD drying	Hot-air drying	Vacuum drying	Freeze drying
SMER (kg water / W h)	1.0-4.0	0.1-1.3	0.7-1.2	0.4 and lower
Operating temperature range (°C)	-10 to 80	40 to very high	30-60	-35 to >50
Operating % RH range	10-80	Varies depending on temperature	low	low
Drying efficiency (%)	Up to 95	35-40	Up to 70	Very low
Drying rate	Faster	Average	Very slow	Very slow
Capital cost	Moderate	Low	High	Very high
Running cost	Low	High	Very high	Very high
Control	Very good	Moderate	Good	Good

The heating of air from temperature T_A to T_B is represented by the line AB. During heating, the absolute humidity remains constant at H_A whereas the relative humidity falls from h_A to h_B. This low relative humidity removes moisture from the materials. As air moves through the material bed it absorbs moisture. Under adiabatic drying, sensible heat in the air is converted to latent heat and the change in air conditions is represented along a line of constant enthalpy, BC. The air will have increased in both absolute humidity, H_C, and relative humidity, h_C, but fallen in temperature, T_C.

The absorption of moisture by the air would be the difference between the absolute humidities at C and B i.e H_C-H_A. If unheated air was passed through the bed the drying process would be represented along the line AD.

According to Prasertsan & Saen-saby (1998) "the relative humidity of the air, if not controlled, will depend on the absolute humidity of the ambient and the drying temperature. At the final stage of drying, there will be little difference of the moisture ratios at the inlet and outlet of the drying chamber. The corresponding temperature difference will also be minimal. All these will result in ineffective drying and low thermal efficiency. However, with heat pump drying, there is control of the moisture and temperature of the air as well as heat recovery. In this way, heat pump dryer can improve the product quality while using less energy." Figure 2 shows the components arrangement and the psychrometric chart of a typical heat pump drying process. The figure shows how the drying air is dehumidified before its further passage through the material, thereby offering an advantage over conventional drying.

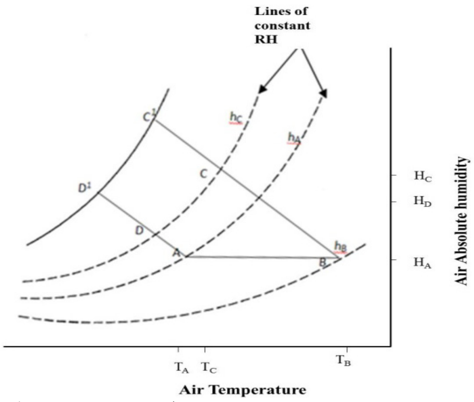

Figure 1: Pyschrometric representation of the conventional air drying system. Adapted from FAO (1994)

3. QUANTIFICATION OF PERFORMANCES DURING HEAT PUMP DRYING

According to Yagcioglu et al. (2001), the goals of drying process research in the food industry may be classified in three groups as follows: (a) economic considerations, (b) environmental concerns and (c) product quality aspects. In addition, heat pump drying technology is environmentally friendly in that gases and fumes are not given off into the atmosphere at the drying site (Nipkow & Bush, 2009). The condensate can be recovered and disposed of in an appropriate manner, and the potential also exists to recover valuable volatiles from the condensate (Perera & Rahman, 1997; Patel & Kar, 2012). The quality attributes of heat pump dried products are presented here.

3.1. Quality

Carrington (2008) itemized three features of heat pump drying technology that help in controlling quality characteristics from deterioration as follows:

- The ability to operate at an absolute humidity less than that of the environment.
- The ability to select the temperature to be less or above the environmental temperature
- The ability to dry in a non-vented chamber using a modified drying atmosphere.

The quality of dried products as enhanced by heat pump drying is comprised of a number of physical, chemical and sensory characteristics discussed as follows:

≡ **Microbial safety**

Quality deterioration caused by microorganisms is undesirable commercially, because they limit shelf life or lead to quality complaints. Drying helps in reducing or overcoming potential microbial damages. With heat pump drying, microbial safety are minimized by ensuring that all raw materials conform to recognized standards of preparation (Carrington, 2008). Heat pump dryers are able to enhance microbial safety in the foodstuffs by maintaining the relative humidity data at acceptable low level. Also, the operating temperature of heat pump dryers is not limited by the environmental humidity, Moreover, Britnell (1994) found that air recirculation in heat pump dryers was not a significant problem for commercial fruit and meat products in Australia, the total bacterial count being typically less than 10^3 per gram of product. However, to guide against microbial activity build up, sterilization must be done as and when due.

≡ **Colour**

Colour degradation is a major cause of loss in food drying. The color of foods is important to their acceptability. Athough, sulfating agents inhibit both enzymatic and non enzymatic browning (NEB) reactions, their use is surrounded by health and safety concerns. However enzymatic browning in the drying of peach halves can be reduced without the use of sulfites by reducing the relative humidity (20%) when the moisture content is high (2kg/kg dry matter) by increasing the air velocity. Mumjumdar (1997) observed the need to reduce the temperature towards the end of the drying cycle to avoid NEB. This strategy is relevant to heat pump dryers because the humidity can be controlled independently of the environment.

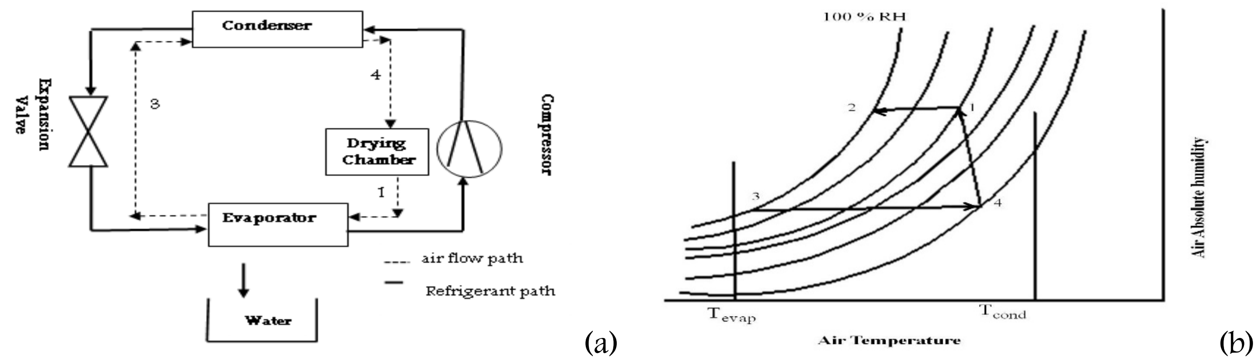

Figure 2. Heat pump dryer (a) Component arrangement (b) Process air on psychrometric chart. Adapted from Prasertsan & Saen-saby (1998).

Also, drying of fruits under nitrogen has been found to be effective in inhibiting browning during the critical initial drying period when the moisture content is high. This shows that there is possibility of using modified atmospheric heat pump drying to produce high quality fruits and vegetables. Another way to achieve non enzymatic browning in banana and other fruits is by using heat pump dryer to produce specific temperature-humidity schedules (Carrington, 2008).

≡ **Ascorbic acid content (AA), volatile compound and active ingredients retention**

The impact of constant temperature drying on product quality is well recorded. Most of the product quality parameters such as NEB and AA content are often manifested by a progressive loss with increasing temperature. It was shown that with proper selection of the temperature schedule, the AA content of the guava pieces can be up to 20% higher than that in the isothermal drying without significant enhancement in drying time. However, results from Perera and Rahman (1997) indicated that using reduced air temperatures at the onset of drying as in the case of heat pump drying followed by temperature elevation as drying proceeds yield a better quality product.

The concentration of volatile compound is usually increase by drying, particularly at lower temperatures typical of heat pump drying. Sunthovit et al. (2007) evaluated the effects of different dryer types namely cabinet dryer, tunnel dryer and heat pump dryer on the composition of volatile compounds of dried nectarine. The result indicated that heat pump dryer is the best system for the preservation of volatile compounds in sliced dried fruits in terms of lactones and terpenoids of all the three. Also, the retention of total chlorophyll content and ascorbic acid content in sweet green pepper was observed by Pal et al (2008) to be more in heat pump–dried samples with higher rehydration ratios and sensory scores than hot air dryer.

≡ **Aroma and flavor loss**

Drying methods that employ lower temperature do provide higher concentration of key aroma compounds (Mujic et al., 2012). Ginger dried in a heat pump dryer was found to retain over 26% of gingerol, the principal volatile flavor component responsible for its pungency, compared with the rotary dried commercial samples that have only about 20% (Carrington, 2008). The higher volatile retention in heat pump-dried ginger may be due to reduced degradation of gingerol when lower drying temperatures are used instead of higher convention dryer temperatures. Since HPD is conducted in a closed chamber, any compound that volatilizes will remain within it, and the partial pressure for that compound will gradually build up within the chamber, retarding further volatilization from the product (Perera & Rahman, 1997). According to Carrington (2008), "the color and aroma herbs (e.g., parsley, rosemary, and sweet fennel) can be improved when compared with the commercial products. The sensory values were nearly doubled in case of heat pump dried herbs compared with commercially dried products".

≡ **Viability**

Drying with oxygen-sensitive materials such as flavor compounds and fatty acids can undergo oxidation, giving rise to poor flavor, color, and rehydration properties. Cardona et al., (2002) study on heat pump dehydration of Lactic Acid Bacteria (LAB) determined under what preparation and drying conditions LAB can be dehydrated in a heat pump dryer without unacceptable deterioration of viability and activity. The result indicated that heat pump dehydration of LAB gave favourable results like the costly freeze drying method. Use of modified atmospheres obtainable with heat pump drying to replace air would allow new dry products to be developed without oxidative reactions occurring (Perera & Rahman, 1997) thereby producing seed with a high proportion of products with germination properties.

≡ **Rehydration**

During drying, important changes in structural properties can be observed as water is removed from the moist material. Rehydration is a process of moistening dry foods materials. In most cases, dried foods are soaked in water before cooking or consumption, therefore rehydration is a very important quality criteria. Factors affecting the rehydration process include porosity, capillarity and cavity near the food surface, temperature, trapped air bubbles, amorphous crystalline state, soluble solids, anion and pH of soaking water, dryness. Faster rehydration had been attributed to apple slices dried with a modified atmosphere heat pump dryer (Hawlader et al., 2006. Also, in another study, heat pump and microwave vacuum–dried tomato slices showed comparatively higher rehydration ratios than hot air– and solar cabinet–dried slices (Gaware et al., 2010).

≡ **Shrinkage**

Shrinkage occurs first at the surface and gradually moves to the bottom with an increase in drying time. The cell wall becomes elongated, as drying proceeds at higher temperature; cracks are formed in the inner structure. From microscopy, it was found that shrinkage of apple slices dried in convection is significantly an-isotropic, while less damage to the cell structure during freeze drying leads to more isotropic deformation (Rahman, 2008). Heating produces major changes in structure of products. Shrinkage occurs because food polymers cannot support their weight and, therefore, collapse under gravitational force in the absence of moisture. Heat pump drying however involves drying at a low temperature, making shrinkage less pronounced.

3.2. Drying Efficiency

The performance of a dryer or drying system is characterized by various indices, including energy efficiency, thermal efficiency, volumetric evaporation rate, specific heat consumption, surface heat losses, unit steam consumption, and others which were defined to reflect the particularities of various drying technologies (Kudra, 2012). Energy efficiency, the ratio of energy required (Er) to energy supplied (Es) in drying is very important because energy consumption is a very significant factor of drying costs (Jangam & Mujumdar, 2010). Due to the complex relationships of the food, the water, and the drying medium i.e. the air, a number of efficiency measures can be worked out, each appropriate to circumstances and therefore selectable to bring out special features important in the particular process. Efficiency calculations are useful when assessing the performance of a dryer, looking for improvements, and in making comparisons between the various classes of dryers which may be alternatives for a particular drying operation (Earle & Earle, 2004). Energy efficiencies are meant for providing an objective comparison between different dryers and drying processes. There are three groups of factors affecting drying efficiency (FAO, 1994)

- » those related to the environment, in particular, ambient air conditions;
- » those specific to the crop;
- » those specific to the design and operation of the dryer.

For HPD systems, drying efficiency is a measure of the quantity of energy used to remove one unit mass of water from the product, normally measured in kJ kg/water or kWh kg/water.

Air-drying efficiency, η can be defined by Eqn. 3:

$$\eta = {(T_1 - T_2)}\big/{(T_1 - T_a)} \qquad (3)$$

where T1 is the inlet air temperature into the dryer, T2 is the outlet air temperature from the dryer, and Ta is the ambient air temperature. The numerator is a major factor in the efficiency [13]. Energy efficiency is also the ratio of the latent heat of evaporation of the moisture removed to the drying air heat input.

3.3. Coefficient of Performance (COP)

Coefficient of performance (COP): The efficiency of the HPD is indicated by compressor cooling coefficient of performance (Mujic´ et al, 2012). COP can be used to evaluate the amount of work converted into heat for two different system operations: cooling and for heating. For a heat pump, the heat transfer $\dot{Q}_{out}$ from the system to the hot body is desired, and the coefficient of performance is expressed as Eqn 4, where $\dot{W}_{cycle}$ is the electrical power input of the compressor.

$$COP_{hp} = \frac{\text{Desired Output}}{\text{Required Input}} = \frac{\text{Heat added}}{\text{Work required}} = \frac{\dot{Q}_{out}}{\dot{W}_{cycle}} \qquad (4)$$

3.4. Specific moisture extraction ratio, SMER

An alternative indicator of the energy efficiency for heat pump dryers is the specific moisture extraction ratio which is measured as in Eqn. 5:

$$\text{SMER (kg/kW·h)} := \frac{\text{Amount of water evaporated}}{\text{Energy used}} \quad (5)$$

The SMER can be calculated either as an instantaneous value or as an average value during drying (Raghavan et al, 2005). During the drying process, the SMER value decreases as the removal of moisture becomes more difficult due to smaller water vapor deficits at the surface of the product. For heat pump dryers, the SMER value can be above the theoretical maximum value. The energy efficiency of HPD can be reflected by the higher SMER values and drying efficiency when compared to other drying systems as shown in Table 1. Consequently, higher SMER would then be translated to lower operating cost, making the payback period for initial capital considerably shorter. Other definitions of specific moisture extraction rate with respect to the compressor power are provided by (Carrington, 2008). The following suggestions were recommended by Strommen and Eikevik (2003) for maximizing the capacity and efficiency of a heat pump dryer:

» use of continuous, instead of batch drying so that the system can be operated at stable optimal conditions,
» air flow should be counter current instead of cross flow or co-current relative to the product movement to maximize the relative humidity at the dryer outlet and to match the drying characteristics of the product,
» the inlet temperature of the dryer should be maximized in accordance with the product requirement,
» the refrigeration capacity should not be oversized so as not to reduce the relative humidity and a consequent reduced smer.
» if possible, select the evaporating and condensing temperatures to optimize the product of COP and the thermal efficiency.

3.5. Exergy

Exergy analysis is a useful tool that can be successfully used in the design of an energy system and provides the information necessary to choose the appropriate component design and operating procedure (Erbaya et al, 2013). Exergy efficiency has been used rather than the energy efficiency in the performance analysis of food process in heat pump dryers, particularly to indicate the possibilities for thermodynamic improvement. It is defined as the maximum amount of work that can be produced by a stream of matter, heat, or work as it comes to equilibrium with a reference environment (Erbaya et al, 2013). Information on exergy is effective in determining the processing plant and operating cost as well as energy conservation, fuel versatility, and pollution associated with the process. Using an exergy analysis method, the magnitudes and locations of exergy destructions (irreversibilities) in the whole system can be identified.

3.6. Drying Rate

In air drying, the rate of removal of water depends on the conditions of the air, the properties of the food and the design of the dryer. Drying rate is expressed as follows:

$$DR = \frac{m_t - m_{t+\Delta t}}{\Delta t} \quad (6)$$

where m_t is the mass at time t. drying rates would decrease as moisture content decreases[21]. Factors affecting the drying rate will vary slightly depending upon the type of drying system used. Wilhelm et al[25] suggested the following factors to be considered:

1. nature of the material: physical and chemical composition, moisture content, etc.;
2. size, shape, and arrangement of the pieces to be dried;
3. wet-bulb depression or relative humidity, or partial pressure of water vapor in the air (all are related and indicate the amount of moisture already in the air);
4. air temperature; and
5. air velocity (drying rate is approximately proportional to $u^{0.8}$).

In general, the drying rate decreases with moisture content, increases with increase in air temperature or decreases with increase in air humidity. At very low air flows, increasing the velocity causes faster drying but at greater velocities the effect is minimal indicating that moisture diffusion within the grain is the controlling mechanism[21].

3.7. Specific energy consumption

The Specific energy consumption is estimated by considering the drying time involved and energy utilization by the various components of the dryer. It is expressed in terms of MJ/kg of water removed and used as one of the factors in the optimization of process parameters. According to

Jokiniemi et al. (2011), it can be calculated by integrating the energy use and by calculating the moisture removal amount as follows in equation 7:

$$Qs = \frac{Qh}{\Delta G} \quad (7)$$

Where Qs is Specific energy consumption of drying; Qh is Energy consumption of drying air; ΔG is the mass of evaporated water.

4. ECONOMICAL ROLE AND COST OF HEAT PUMP OPERATION

Heat pump dryers are known to be cost effective in many drying applications because it can extract and utilize the latent energy of the air and water vapor for product drying (Mujic et al, 2012). Also, from experience, they consume only about half of the electricity of conventional condenser dryers (Nipkow & Bush, 2009). Earlier published works in the area of heat pump assisted grain drying found the concept to be mechanically feasible but not attractive economically due to the low fuel prices prevailing at the time (Jokiniemi et al. 2011). However, Prasertsan and Saen-saby (1998) showed that HPD had the lowest operating cost when compared to electrically-heated convective dryers and direct-fired dryers. For heat pump dryers, the total cost of removing a liter of water from a product is considerably lower at longer hours than at shorter hour. Also, Sosle et al. (2001) confirmed that HPD is useful for materials with high initial moisture content and in regions with high humidity of ambient air. HPD is preferable where high value/quality retention outweighs other considerations. The economic value of purchasing a heat pump depends on the relative costs of the energy types that are consumed and saved.

Jangam and Mujumdar (2010) observed that the capital and running costs of heat pumps can be reduced by using heat pumps only over the initial drying period beyond which the dehumidified drying air does not enhance the drying rate any longer. Also, Mujumdar (1997) showed that it is necessary to make heat pump drying technology more cost effective by reducing both the capital costs (i.e., smaller heat pumps) and operational costs (i.e. reduced running time to decrease cost of electricity utilization or supplementary use of renewable energy such as solar energy where possible). Furthermore, heat pumps with multiples modes of heat input and intermittent operation allow the use of smaller heat pumps to service more than a single drying chamber for simultaneous drying of different products. Finally, using mathematical models, concurrent and sequential application of heat by radiation, conduction and convection can enhance the drying kinetics while improving quality at reduced capital and operating costs.

5. CONCLUSION

This paper has reviewed the principles and potentials of heat pump drying of fruits and vegetables. It has been shown in this paper that heat pump dryers are promising technologies that maintains product quality and reduce energy consumption of drying, particularly for high value products like fruits and vegetables. The application of heat pump drying contributes positively to the following fruit and vegetables quality attributes including improved microbial safety, better colour, vitamin C retention, enhanced volatile compound, aroma and flavor compounds, rehydration and texture. Finally, some factors that can make heat pump drying cost effective are elucidated. Adoption of heat pump drying technology for drying of fruits and vegetables in Sub Sahara Africa will improve product quality and reduce energy consumed in the process.

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