



Research Paper

Heat and mass transfer modeling for fruit drying: A review

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ABSTRACT

In this review, coupled heat and mass transfer phenomenon (drying) is discussed. Drying is an effective method for food preservation. Drying could retain quality end products, which is challenging because all fruits are variable in structure, so, heat and mass transfer modeling is a useful technique to deal with it. This can only be done by selecting the right type of drying equipment and understanding the science behind drying including the thermal properties of the fruit. The drying process has many effects on different heat sensitive fruits components and equipment (sensors etc.) as well, which result into increase in maintenance cost, diffusion rate goes to critical limits. Selection of an appropriate drying method and equipment is most important regarding product quality and process economic value. Modeling of the drying process considering different drying parameters and their effects on the final quality of products and economic importance has been discussed. We should have knowledge about the drying mechanics. So, this knowledge of heat and mass transfer process for fruit drying helps to identify best-operating conditions and saves the maximum amount of energy.

Key words: Modeling, coupled heat and mass transfer process, fruit drying.

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INTRODUCTION

Food is the necessity for mankind as it provides energy, growth, and repair to the body (Potter and Hotchkiss, 2012). Most of the agricultural commodities are seasonal. Fruits are present in bulk during their season, but during the offseason, this fruit is not available because it gets wasted due to improper storage techniques. About 40% of the fruit production in Pakistan is wasted due to improper handling and preservation techniques (Sohail et al., 2015). Fruit production in Pakistan in 2016-17 was 5,685,000 tons: 440,000 tons were exported and 2,274,000 tons got wasted (Ahmad, 2009). Agricultural products can be categorized based on the water content present in them: perishable, semi-perishable and non-perishable products. Products have different shelf life depends on their perishability level (Jamalzadeh et al., 2011). Water is a major constituent of fruits and even after harvesting, the maturing process of climacteric fruits continues. This water leads the fruits to get spoil due to the autolysis and the microbial attack. Fruits are decayed due to biochemical reactions, microbial growth, enzymatic activity and

proliferation, and water is the factor to do so (Finley et al., 2018). Chemically, fruits get spoiled due to the non-enzymatic browning and oxidation. To consume seasonal fruits throughout the year, it must be protected from such as ice creams, frozen desserts, sweets, bakery products, baby foods, jellies, crackers, horseradish such as ice creams, frozen desserts, sweets, bakery products, baby foods, jellies, crackers, horseradish. Noodles, which are a staple food of some Asian countries, are found in the market in instant form and all fruits in it are in the dried form (Gulia et al., 2014). Some of the fruits are converted to powder for use as ingredient in food recipes. Food insecurity includes many factors and postharvest losses is one of them. Fruit processing is the most important form of improvement from an agricultural point of view, to make the economy of country strong, increase export and develop new value-added products and dried fruits (Fellows, 2009). Drying is an efficient method for preserving the fruit. To prolong its shelf life for months, dry it by proper means and in an hygienic environment otherwise sensory parameters such

as color, flavor, texture and sound start to degrade, and the fruit becomes as waste.

Drying is the removal of moisture from fruit products up to a certain level and dehydration is the bone-dry condition of that product. Drying is a physical process performed to stabilize fruit as biological changes in fruit lead to deterioration. Cost of transportation decreases, and handling becomes easy as its weight and volume reduce, consumption is followed with calculated rehydration. Drying slows down the microbial and enzymatic activity by lowering water activity. Apple has a water activity of 0.85-0.95 and drying reduces water activity to about 0.5 (Krokida et al., 2003).

Akoy et al. (2008) conducted a research to check the drying kinetics and changes in the color of mango slices, when dried under different temperatures. Fresh mangoes were kept in a room at $25 \pm 2^\circ\text{C}$ at 50% relative humidity for 5 days. Mangoes were washed, peeled, and then size reduced to slices using a slicer with 3 mm thickness and 50 mm diameter. Cross flow dryer was used which consisted of a centrifugal fan, drying chamber, temperature control unit, and a heating unit. Convective air drying was at 1.5 m/s air velocity, 135°C temperature, 2 h time and moisture content of sliced mangoes 82.5% (wb). Weight loss determination was after every 30 min. At the end of drying, 9% moisture content (wb) was achieved, determined by weight loss formula. Quality parameters, such as color and rehydration ratio, were evaluated. Firstly, the color was measured via Chroma meter and compared with the color shade of fresh mango pulp which was considered as a standard. Rehydration ratio was calculated using the AOAC method. 5 g of dried mango was immersed in 50 ml of distilled water for 30-60 min. After filtration of that rehydrated pulp, the filtrate was weighted, and the rehydration ratio was calculated by inserting values in a formula. Finally, it was concluded that drying time changes fruit quality and color. Optimum drying temperature for mango slices was 80°C .

Heat transfer

The temperature difference is the driving force for heat transfer. So, heat transfer exchanges thermal energy from high concentration to low concentration between physical systems. There are three modes of heat transfer namely, conduction, convection, and radiation. Mostly conduction and convection modes are used for drying of fruits. Radiation is a modern technique having high quality dried products, but the capital cost is high which makes it infeasible in developing and underdeveloped countries, however, these techniques are used in developed countries. Energy in drying is in the form of heat, and heat is the simplest form of energy and travels from hotter to cooler medium. Heat leaving the system towards surrounding gives the negative heat transfer rates and vice versa.

Generally, heat transfer is:

$$Q = mC_p \Delta T \quad (1)$$

One important thing to consider is $C_p = C_v$ for solids and liquids (Singh and Heldman, 2001).

Mass transfer

Mass transfer is the movement of chemical species from high concentration region to low concentration region and the presence of these two regions are necessary, but fluid flow moves from one location to another and occurs on a macroscopic level. The fluid flow needs pressure difference and mass transfer needs concentration difference as their driving force. Modes for mass transfer are conduction and convection only. Fick's second law for mass transfer is usually studied to understand the mass transfer rates. There are different types of mass transfer conduction (diffusion) namely; ordinary diffusion, forced diffusion, Knudsen diffusion, surface diffusion and Brownian motion, and each have their applications for respective products (Basmadjian, 2003).

Thermal properties of fruits

Thermal properties of the fruit are listed hereafter (Mohsenin, 1980).

Specific heat

This is the quantity of heat required to change a unit temperature of a unit mass of the product, without changing its original state:

$$C_p = \frac{Q}{m(\Delta T)} \quad (2)$$

Its units are $[\text{kJ}/\text{kg}^\circ\text{C}]$. Specific heat of product is needed in the design of drying equipment and processes. Specific heat is directly proportional to the moisture content of the product. Specific heat can be determined using numerical methods presented by Choi and Okos in 1986. The methods for specific heats determinations are: Method of Mixture, Method of Guarded Plate, Method of Comparison Calorimeter, Adiabatic Agricultural Calorimeter, and Differential Scanning Calorimeter (DSC) (Sahin and Sumnu, 2006).

Thermal conductivity

This is the quantity of heat that is conducted through per

unit thickness, per unit time of the product, if two materials are having a unit temperature difference:

$$K = \frac{W}{m^{\circ}C} \quad (3)$$

Its units are $[W/m^2\text{ }^{\circ}C]$. Thermal conductivity is useful in determining heat transfer rates. Thermal conductivity for water at 20°C is 0.597 $W/m^{\circ}C$. Dried fruits have lower thermal conductivity values due to the porous structure. Thermal conductivity can also be calculated using Choi and Okos (1986) numerical model. Singh and Heldman (2001) also developed mathematical models to determine thermal conductivity for anisotropic food products which are direction dependent as parallel to fibers or normal to fibers slices of mango. Different types of models are also made to calculate thermal conductivity, such as Parallel Model, Series (perpendicular) Model, Krischer Model, Maxwell-Eucken Model and Kopelman Model (Progelhof et al., 1976).

Thermal diffusivity

This is the ratio of thermal conductivity to specific heat and density:

$$\frac{\text{Heat Conduction}}{\text{Heat Stored}} = \frac{k}{\rho C_p} \quad (4)$$

Its units are $[m^2/s]$. Thermal diffusivity can be calculated by inserting values of thermal conductivity, specific heat, and density. Density can be calculated from Choi and Okos (1986a) mathematical formulas by just inserting the value of the temperature of the product. The methods for determining thermal diffusivity are Indirect Prediction Method, Direct Measurement Method and Dickerson method (Magee and Bransburg, 1995).

Drying process

Drying is a coupled heat and mass transfer mechanism. There are different types of drying techniques used in this modern era. Food Engineers are working hard to develop more efficient methods for drying of perishable agricultural products that minimally alter its quality. There are different drying methods and mostly, hot air drying is used. Some of the drying methods used are: direct sun drying, solar tunnel dryer, solar augmented drying, freeze drying, microwave drying, vacuum drying, foam mat drying, puff drying, radiant heating dryer, infrared dryer, spray drier, fluidized dryer, Oregon tunnel dryer, and dehydro-freezing (Mujumdar, 2000). Selection of a suitable drying method is

very important for final product quality and operating cost. Some of the drying methods require huge installments and high energy expenses which make them not suitable.

Ndukwu et al. (2017) dried two varieties of cocoyam slices namely; *Colocasia esculenta* (COE) and *Xanthosoma sagittifolium* (white flesh-NX01, red flesh-NX02) through convective drying mechanism of sun drying and oven drying. Researcher checks the retention of the vitamin after drying. Heat and mass transfer parameters such as convective heat and mass transfer coefficient, diffusivity coefficient, activation energy, energy consumption, drying rate and volume shrinkage ratio were also monitored. Cocoyam was sliced. Temperatures of 50, 60 and 70°C were recorded with humidity of 7.8, 5.1 and 3.6% and with a constant air velocity of 0.02 m/s. Thermocouple records the temperature inside the slices which was 22-22.5°C. At 30 min, interval weight loss was monitored. For all three varieties of cocoyam slices, the coefficient for mass transfer was in the range of 1.17973-3.5828 W/m^2 at temperature of 50, 60 and 70°. COE variety showed the highest rate for heat and moisture transfer and the lowest rate was shown by red fleshNXO₂. Riboflavin showed the highest retention level with 92.25-100% while thiamine had the lowest retention level with 70.13-82.3%.

Drying causes nutritional, physical, chemical and sensory changes in fruit that depend on heat and mass transfer parameters intensity. Many compounds in fruits are temperature dependent, due to their heat-sensitive properties. So, an optimum amount of heat is provided to avoid quality deterioration. The efficiency of the drying process depends on the internal and external parameters provided to it. Internal parameters include thermo-physical properties, sorption-desorption characteristics, porosity, density and permeability of the fruit material being dried. External parameters include relative humidity, temperature, and air velocity (Maroulis et al., 1995). Modern technologies, such as infrared radiation, pulsed electric field, high-pressure processing and contacting ultrasound system, improve the drying process rate and quality parameters for the product being dried and reduce the energy requirement. These technologies are mostly coupled with hot air drying that enhanced the drying process (Figure 1).

Drying rate and product properties depend on the drying parameters, such as temperature, air velocity, and relative humidity, provided to it (Peishi and Pei, 1989). Kumar et al. (2012) suggested that during the drying of food product, both heat and mass are in motion as shown in Figure 2.

Modeling of drying mechanism

Fruit in its biological structure is variable and complex. Every fruit needs a different model to dry it by retaining quality, which is challenging. So, modeling and simulation

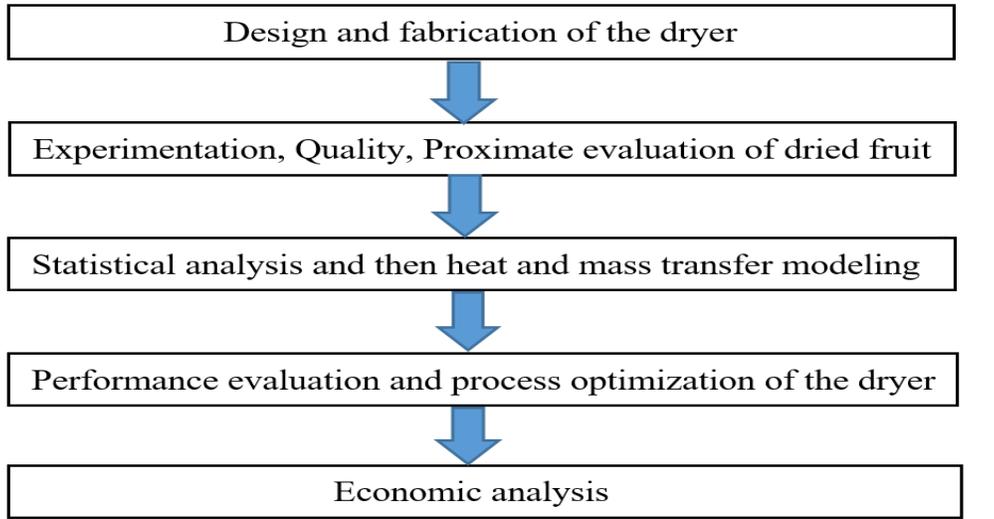


Figure 1: Main steps for developing an effective drying process.

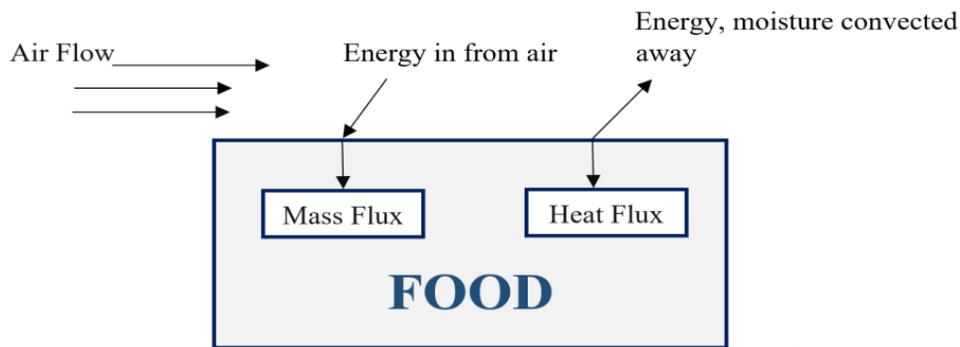


Figure 2: Schematic diagram of heat and mass transfer during drying of food material.

are a useful technique to deal with it. A mathematical model based on heat and mass transfer is used to study the behavior of drying operation. Assumption related to mass transfer parameter, that is, material properties, transport equation, initial and boundary conditions and PDE (Partial Differential Equation) is solved and these models are used to simulate process variables. A mathematical model is used to maintain quality and to optimize dryer efficiency. The driving force for drying is the temperature difference that causes moisture transfer, and concentration gradient plays a key role in drying. Coupled heat and mass transfer approach are used for mathematical modeling. A mathematical model for heat and mass transfer is mostly developed based on Fick’s law and Fourier law. Theoretical and empirical models are used currently (Rastogi et al., 2002). Different mathematical models are made for modeling of the drying process (theoretical models etc.). Software such as CFD (Computational Fluid Dynamics), COMSOL Multi-physics is mostly used for simulation:

$$\begin{aligned}
 \dot{m}_{conv} &= h_{mas} A_s (C_s - C_\infty) & \text{-----(5)} \\
 \dot{Q}_{conv} &= h_{conv} A_s (T_s - T_\infty) & \text{-----(6)}
 \end{aligned}$$

Mass convection
Heat convection

Mass transfer coefficient
Heat transfer coefficient

Concentration difference
Temperature difference

Villa-Corrales et al. (2010) conducted heat and mass transfer analysis of mango fruit using numerical method. Dryer consists of a tray, heat exchanger using a resistance coil and a drying chamber. Air velocity and air humidity were fixed, and the temperature was controlled via sensors installed at inlet and outlet points of the air passage. A K-type thermocouple measures sample temperature. All its components are connected to a digital system to control the process. Ataulfo mango selection considerations for this experimentation include its organoleptic properties, handling resistance, fiber content, sugar content and aroma. An

absence of stability, color, and size was considered. Washed mangoes were kept for 24 h in a room at $24 \pm 3^\circ\text{C}$. Moisture content 83.5-85.2%, TSS 13.2-22°Brix mango slices with 40 mm long, 15 mm wide, and thickness of 2, 3, 4, and 5 mm using slicer equipment and 5 out of 6 sides of mango slices were covered with a plastic film. To check the water effective diffusion, parallel to fibers and normal to fibers shapes of mango were cut. Moisture diffused through only one side (upper side) which was uncovered. During drying, temperature levels were 50, 55, 60, 65 and 70°C , relative humidity $15 \pm 2\%$ with 0.2% air velocity and 13.2-22°Brix maturity level. Firstly, from the experimental results, it was concluded that drying time and the temperature had an inverse relationship. Secondly, 1 mm increase in thickness reduces 4.5% drying rate. Thirdly, moisture diffusion depends on the maturity level of mango pulp. With more maturity, the pulp becomes viscous and needed more energy to escape moisture from the pulpy juice. The drying for mango is slow inside the slice as compared with the boundary layer because of the higher moisture gradient. Fick's second law and Fourier law were used for numerical calculations. The activation energy was calculated as 23.45 kJ/Kmol , effective diffusivity $4.41 \times 10^{-10} - 5.95 \times 10^{-10} \text{ m}^2/\text{s}$, and moisture diffusivity $19.40 \times 10^{-10} - 1.04 \times 10^{-9} \text{ m}^2/\text{s}$.

Conclusions

In this review article, a simultaneous heat and mass transfer process for the drying of fruits is discussed. Fruits composed of high-water content and heat sensitive compounds are difficult to dry, by retaining quality. Understanding heat and mass transfer process and its process parameters are mandatory for the efficient drying process, which minimally affect the sensory and other quality parameters of the subjected fruit. Calculations for heat and mass transfer greatly help to optimize the efficiency of drying unit, drying rate as well as reduces energy consumption and also help to identify the most appropriate operating conditions.

Symbols used

Q = Heat transfer (kJ)
 m = Mass of fruit material (kg)
 C_p = Specific heat of the material being dried ($\text{kJ/kg}^\circ\text{C}$)
 ΔT = Temperature difference ($^\circ\text{C}$)
 K = Thermal conductivity ($\text{W/m}^2^\circ\text{C}$)
 ρ = Density (kg/m^3)
 $T_s - T_\infty$ = Temperature difference across thermal boundary layer
 $(C_s - C_\infty)$ = Concentration difference across concentration boundary layer
 A_s = Surface area

h_{conv} = Heat transfer coefficient
 h_{mass} = Mass transfer coefficient
 \dot{m}_{conv} = Mass transfer rate
 \dot{Q}_{conv} = Heat transfer rate

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