Review Article

A Comprehensive Review on the Drying Kinetics of Common Tubers

Flordeliza H. Cosme-De Vera
School of Chemical, Biological, and Materials Engineering and Sciences, Mapua University, Manila, Philippines

Allan N. Soriano and Nathaniel P. Dugos
Chemical Engineering Department, College of Engineering, De La Salle University, Manila, Philippines

Rugi Vicente C. Rubi*
Chemical Engineering Department, College of Engineering, Adamson University, Manila, Philippines

* Corresponding author. E-mail: rugi.vicente.rubi@adamson.edu.ph

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Abstract
Sun-drying has been conventionally used in the production of tuber-derived commodities such as cassava, potato, sweet potato, and yam. Recent developments in the drying process involves the use of different drying equipment to improve quality and profitability. The importance of drying parameters in the operation of drying equipment necessitates drying kinetic studies on common tubers. This article aims to review the drying kinetics studies conducted on common tubers. Particular interest is on the effect of the drying process parameters like temperature and velocity of heating air medium, the physico-chemical pretreatment method, and sample preparation on the drying rate and time. The different best fit drying kinetic models for specific tubers have also been extensively studied. The role of drying process parameters and best fit model equations on the design of the drying equipment has been emphasized.

Keywords: Drying kinetics, Drying parameters, Model equation, Pretreatment, Tubers

1 Introduction

Good preservation practice in the agricultural and food industry normally employs drying techniques. This ensures the reduction of moisture content, prevention of microbial contamination and physical deterioration, and promotes longer shelf life [1]. Sun drying has been primarily used and it utilizes the synergistic effect of sun and wind energy. In this method, the common tubers of interest (Figure 1) like cassava, yam potato, and sweet potato are stored under direct sunlight or indirect sunlight. For the latter, transparent plastic or films are used as cover for the food items [2]. The food industry that normally manufactures common tubers incorporates an efficient drying process that plays a crucial role in achieving profitability. The production of tuber-derived commodities involves the drying process, the principles of drying phenomenon, and the mechanism involved. The selection of the proper drying equipment is also considered to impact the quality of the tuber products [3], [4]. In a typical drying process, the complexity of heat and mass transfer phenomena is affected by two major parameters. The initial moisture content of the raw material and the drying air temperature medium affect the quality of the product. It is known that the market value, quality, and packaging of a tuber-derived commodity are impacted by the amount of moisture in the final product. Thus,

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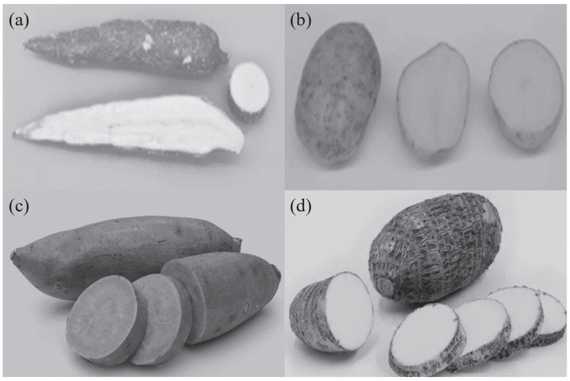

Figure 1: Common agricultural tubers (a) cassava (b) potato (c) sweet potato and (d) yam.

the excess moisture content is considered to be an undesirable property of any tuber product [3].

The drying of tubers involves both physical and chemical changes. Its mechanism starts with the evaporation of the moisture on the surface. The moisture is further removed via absorption to the atmosphere due to the partial water pressure difference between the surfaces at the surrounding. This is followed by the migration of liquid and vapor moisture from the interior to the surface of the sample. It is important to note that during the evaporation (drying), some reactions may occur that result in physico-chemical changes in the desired product. The energy-intensive drying process is typically associated with high operational cost. Hence, a proper understanding of the physical and chemical changes occurring during the process is of vital importance. The physico-chemical properties and related parameters (temperature, thermal conductivity, specific heat capacity, velocity, humidity, and density) of the drying air medium are necessary for studying the drying mechanism. Also, physical morphological properties like size and shape, dimension, structure, porosity, and specific tuber of interest are vital parameters. These factors play a crucial role in the drying kinetics and mechanism [4].

The establishment of a good drying kinetic model allows the quantitative monitoring of physico-chemical changes that occur during the process. The understanding of this phenomenon is essential in the production of quality tuber-derived commodities. The effective drying rate model facilitates learning at the reaction mechanism level. The mathematical consideration associated with proper assumptions and parametric consideration in the design of dryers may result in optimum process design, less energy consumption, and increased profitability [1]. Hence, the objective of this paper is to review different drying kinetics and modeling studies of common tubers such as cassava, yam, potato, and sweet potato and discuss the effects of the drying process parameters on the quality of the products.

2 Effects of Process Parameters on the Drying Rate of Common Tubers

Tubers and tuber-derived products are important food staple and primary sources of carbohydrates in the larger population of the world. Numerous amounts of tuber-derived products serve as food snacks, animal feed, and are also used industrially. Some food products that are readily available in the market are potato chips, crackers, fries, and flour or starch. It is known that tubers are one of the top sources of starch. However their bulkiness and high moisture content of 60–90% pose drawbacks in terms of high transportation cost and short shelf life. These factors affect its market value [5]. To address this concern, food processing typically includes a drying operation to produce products with a certain acceptable moisture content in a suitable packaging condition. The drying rate of tubers is primarily affected by the temperature of the heating air medium (Table 1). Recent studies on the drying kinetics of potato and sweet potato chips typically employ drying air temperature ranging from 30–75°C [6]. Results show that total drying time decreases and the drying rate increases with increasing drying temperature. This is associated with the driving force that initiate evaporation of water from samples and is facilitated by increase in the surrounding temperature [6]. This was also the observation of Duangchuen *et al.* [7] that as the drying air temperature increases, the product moisture content decreases. This is due to the substantial heat supplied at the sample that resulted to a better drying effect. Also, air with lower humidity enhanced drying process at a lower temperature. In addition, the decrease in moisture content as the dry air temperature increases is attributed to the rapid release of a water molecule from the pores of the materials [8]. Results obtained by Pornpraipech *et al.* [9] show that the time required to reduce the moisture content to a certain amount is dependent on the drying air

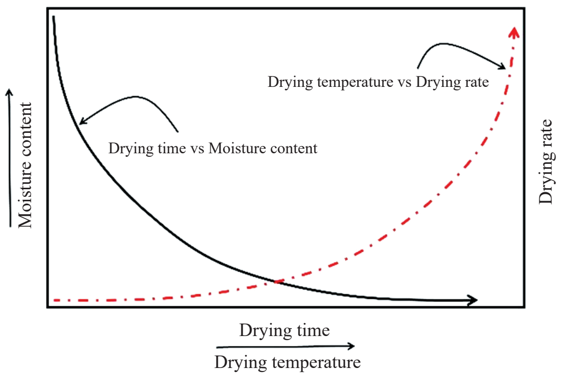

Figure 2: Typical graph of drying time, drying temperature vs moisture content, and drying rate.

temperature. Related studies on the drying of cassava chips also observe that the final moisture content decreased as the temperature increased (Figure 2). This signifies that it is a contributing parameter to the drying rate. Similar results are observed by Lertworasirikul *et al.* [10], Onyelucheya [11], Andrade *et al.* [12], and Xiao *et al.* [13]. They reported that higher drying temperature of the supplied superheated steam result to physical discoloration of samples. This is attributed to the breaking down of starch forming sugar that eventually turns brown. The faster drying process due to the higher drying temperature is associated with the greater heat energy used to vaporize water molecules from the surface of the sample. This is followed by the accelerated diffusion of water molecules from the inner region to the surface [13].

The drying process involves the mass transport owater molecules within the sample to the surface, followed by bulk diffusion from the surface to the surrounding. The drying behavior is affected by the shape and dimension of the sample. In a typical drying process, sample preparation is done by cutting, slicing, and crushing to reduce the total drying time. The work of Naderinezhad *et al.* [6] present that square-shaped potato dries faster than the circle-shaped sample. This confirmed that shape parameter has much impact on the drying rate. It was also reported that the same shape is analogous to the cross-sectional area but would give a higher lateral surface area for a square than circular sample. This resulted in a higher surface exposure to the airflow and subsequently increased the evaporation rate. Furthermore, the effective heat transfer rate indicated by the temperature gradient is better in the square shape that in circular shape. This is due to a higher ratio of perimeter to the cross-sectional area in square-shaped than the circular sample [6]. Also, the selection of the cutting segment (Figure 3) of samples affects the drying rate of the tuber. It was reported that at constant thickness (2 mm) different activation energy was observed at the different cutting segments. The higher activation energy was reported with sample cut at the base segment. This is due to the thicker and harder characteristics as compared to the other

Table 1: Summary of common tubers, sample preparation and drying kinetic parameters

Common Tuber Sample	Sample Preparation	Drying Kinetic Parameters	Ref.
Semi-finished cassava crackers	Cylinder shape (D = 2.5 cm, L=17–20 cm)	D.A. Temp = 50–80°C, Fan speed = 0.18 kW	[10]
Cassava slices	Slices	D.A. Temp < 100°C	[11]
Cassava chips	Rectangular shape (1–2 × 4–5 cm) Circular shape (D = 5–8 cm),	D.A. Temp = 60–120°C	[9]
Fermented Ground Cassava	Ground cassava	D.A. Temp = (115–230°C) Inlet air velocity = (0.83–1.55 m/s),	[8]
Potato chips	Slices, 3.5 ± 0.3 mm in thickness.	D.A. Temp > 80°C	[40]
Potato pulp waste	Homogenized liquid	D.A.Temp = 50–70°C	[39]
Sweet potato slices	Slices	D.A. Temp = 45–70°C. air velocity 1.60 and 1.81 m sec-1	[6]
Sweet Potato Chips	Chips, 1.5 mm thickness	D.A. Temp = (40, 50 and 60°C	[33]
Biofortified sweet potato	Slices, 4.6 × 4.0 × 0.2 cm	D.A. Temp = 45–75°C	[41]
Arrowroot Starch	Milky liquid pressed from pulp	D.A. Temp = 30°C to 65°C, air veliocity from 0.4 to 0.6 m/s	[42]
Yam slices	Slices, 12.0 ± 0.5 mm thickness	D.A. Temp = 50–70°C	[43]
Yam	Circular (3.19 cm) and square slices (5.6 × 5.6 cm)	D.A. Temp = 40 to 70°C	[12]
Yam starch	Powder	D.A. Temp = 25 to 45°C	[44]

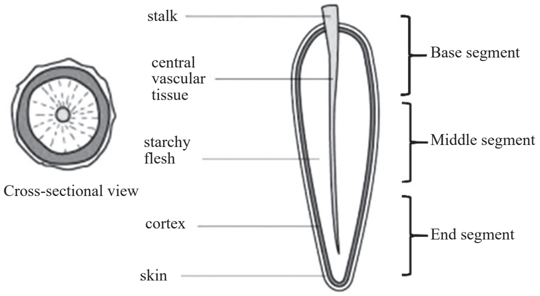

Figure 3: Typical structure of cassava tuber [4].

segments, This result in higher diffusion time of the water molecules from the inside to the surface. The diameter of the segmented samples also influence mass diffusion behavior. The diffusion tendency is higher in the axial direction and the axial cross-sectional area is much larger than the radial cross-sectional area [12]. The previous work of Singh and Pandey [14] reported that as the thickness (5–12 mm) of the sweet potato cube sample increased, the drying time increased. This is due to the increase in the diffusion path. The work conducted by Nasri and Belhamri [15] focused on the effect of shape in the drying of potato in the Maghreb region. Their results show that drying rate is fastest for cylinder-shaped samples, followed by cubical samples, and lastly the parallelepipedic-shaped samples. Faster moisture removal is observed in tuber samples with lower mean diameter size (particle size). It is observed that shorter diffusion distance from the inner region to the surface of the sample favors higher moisture removal at a shorter period of time [10]. For samples with a higher surface area exposed to the heating air medium, there is better heat and mass transport during the drying process [4]. Usually during the drying process as the size of the particle increases its density decreases. This increase in volume is associated with the increase of the interstitial air in the sample [7].

Another factor that influence the drying behaviour of the common tubers is the porosity and porosity transformation of the raw materials. The porosity of the tubers is characterized by the ratio of the void region occupied within the material to the total volume of the material [16]. The initial porosity of common tubers varies between 0.66 to 0.88 and decreases as the drying process progresses. The understanding of porosity and porosity formation is necessary since it affects the qualities of the dried product such as stability, texture and rehydration [16], [17]. Limited studies have been conducted on the influence of the porosity of the tuber sample in the moisture transport mechanism during the drying process. However, it is observed that dense samples with small void space (lower porosity) do not favor mass diffusion of water vapor within the internal structure. Increasing the void space (porosity) facilitates the formation of water vapor in it, and increases the moisture transport rate to the surface of the sample [18]. The high porosity is associated to the higher specific surface area of the particle. However, as the drying time progresses, the porosity of the sample decreases. This limits the rate of moisture transport [16].

A porosity transformation study during drying process has been conducted by Goncalvez *et al.* [19] in the microwave-hot air drying of cassava. They reported that shrinkage in the sample volume is due to contraction stress that affects the porosity of the product. Also, works of Pimpaporn *et al.* [20] on the drying of potato at 80 and 90°C show a uniform pore size distribution in the final product.

The airflow velocity of the drying air medium also contributes to the drying rate of tubers. Faster airflow velocity promotes higher air mass entry into the drying equipment. This results to a faster drying rate. In typical drying operations, forced convection is employed to ensure an efficient drying performance [21]–[23].

The enhanced migration of water molecules from the inner region to the surface is due to a substantial amount of heating air supplied to the samples. The forced convection drying supplies drier air compared to natural convection, This facilitates faster evaporation of the moisture on the surface of the sample. The relative humidity (RH) of the heating air medium also contributes to the moisture content profile of the sample. This affects the drying rate behavior of the tuber. The works of Taiwo and State [8] suggest that the best drying results for drying of fermented ground cassava mash are in the range of 50–60% RH of drying air medium. Ju *et al.* [23] also reported an exponential decrease in the moisture ratio when the RH changes in the range of 20–40%, at 60°C and air velocity of 1.5 m/s. Also, high RH of drying air medium lead to a rapid increase in the temperature of the sample. Again, this facilitates an enhanced driving force for water mass transport and lessens the drawbacks of higher

RH in the drying rate. In the case of the drying process under the falling rate period, the internal resistance controls the migration of water. The RH has no significant impact on the drying rate. This is consistent with the observations reported by Singh and Pandey [14] and Kossaih *et al.* [24]. They observe that drying in the falling rate period exhibits an internal mass transfer phenomenon initiated by diffusion.

3 Effects of Pretreatment on the Drying Rate of Common Tubers

In recent years, the processing of tuber-derived products generally employs some type of pretreatment process before the drying operation. This involves physical operations like blanching, soaking, boiling, peeling, ultrasound, and microwave-assisted pretreatment (Table 2). Blanching is done using a short and mild heat treatment to the tubers sample. The purpose is to do an enzymatic inactivation, physical structure modification, and flavor and nutritional value preservation [25].

On the other hand, chemical pretreatment utilizes chemicals like citric acid, esters emulsions, sodium hydroxide, sodium chloride, potassium, and sodium carbonate. It is shown to be effective in the removal of fibrous waxy barrier on tubers that result in enhanced drying rate [26].

Studies on the sequential soaking-blanching-boiling pretreatment of cassava chips exhibit an initial high rate of moisture removal followed by slower moisture desorption. The drying rate progress as the moisture ratio decrease non-linearly with higher drying time [27]. This is in agreement with the work of Pimpaporn *et al.* [20]. They reported that combined pretreatments of blanching and freezing lead to a shorter drying time than that of unblanched potato samples. This observation is attributed to the structure softening of the potato tissue during the blanching process that facilitates moisture removal. Also, slow freezing promotes the formation of large ice crystals within the potato samples. This leads to the openings of the cell wall and semi-permeable membrane that inhibits moisture transfer during drying [9]. Hidayat and Setyadjit [28] reported the effect of blanching pretreatment on the physico-chemical characteristics of potato powder samples. They reported that the pretreatment affects the yield, color, water, and protein content, and had no significant effect on ash, fat, and carbohydrate content. The effect of superheated steam blanching pretreatment on yam slices was conducted by Xaio *et al.* [13] and showed an increased in the drying rate. On the other hand Ahmed *et al.* [29] reported that chemical pretreatment using sodium hydrogen sulfite and calcium chloride improved the quality of sweet potato flour. Chemical pretreatment of yam flour using 0.28% potassium metabisulphite solution [21] resulted in a significant interaction ($p<0.05$) between pretreatment and drying methods and the functional properties which are associated with the production of high-quality yam flour [26]. Recent pretreatment techniques conducted by Ostermeier *et al.* [30] investigated the applicability of pulsed electric field (PEF) in the pretreatment of common vegetables. They reported that the PEF-pretreated samples showed a 32% reduction in drying time as compared to untreated samples. Also, pretreatment of sweet potato using

Table 2: Summary of pretreatment methods in the drying of common tubers

Tuber Sample	Pretreatment Method	Effects	Ref.
Potato, yam	Microwave-assisted	Increased in hardness in rehydrated apple and potato	[46], [47]
Sweet potato	Hot water and superheated steam blanching, citric acid	Effects on texture, microstructure, and color	[52]
Potato chips	Combined pretreatment	Positive effects on colors, texture (hardness, toughness and crispness) and microstructure	[20]
Potato, potato chips	Blanching and freezing	Shorter drying time	[40]
Yam slices	Blanching	Reduced drying time	[22]
Cassava chips	Soaking and boiling	Enhanced drying rate	[25]
White yam	Microwave and blanching	Positive effect on drying rate	[35]
Arrowroot Starch	Size reduction and pressing	Better starch recovery	[42]
Purple yam slices	Steam blanching and soaking in sodium sulfite solution	Better dried product color	[13]
Sweet potato	Ultrasound-assisted	Change in the microstructure	[51]

ultrasound of 28 kHz frequency and 300 W power for 30 min showed a higher moisture content loss as compared to control samples [31].

4 Drying Kinetics Modeling of Common Tubers

The physical phenomena during the drying process of common tubers is very complex. Proper understanding and knowledge of this complexity as related to the drying kinetics is necessary. The drying operations of some biological materials is fundamental to the selection, design, and optimization of the drying process and equipment. Drying kinetics modeling, which is a useful tool in describing physico-chemical changes quantitatively, is essential in the processing of tuber-derived products. Conducting a full-scale experiment in determining appropriate drying conditions is costly. Drying kinetics study and obtaining the best fit kinetic model equation can aid in identifying appropriate drying methods and to control the drying process. Shown in Table 3 are the obtained drying rate models in common tubers. In the kinetic modeling of common tubers like cassava, the investigation of effective moisture diffusivity is calculated using Fick's diffusion equation for objects with a slab geometry as shown in the following Equation (1):

$$MR = \frac{8}{\pi^2} exp \frac{-\pi^2 D_{eff} t}{4L^2} \tag{1}$$

where: MR is moisture ratio, D_{eff} is effective moisture diffusivity (m^2/s), t is the drying time in (s) and L is half of the slab thickness (m). The method of the slope was used to calculate the D_{eff} and is shown in Equation (2), while the diffusion coefficient was typically calculated by plotting experimental drying data in terms of ln (MR) versus drying time [25].

$$Slope(k) = \frac{D_{eff}\pi^2}{4L^2} \tag{2}$$

The work of Argo *et al.* [38] on the mathematical modeling of the thin layer drying kinetics of cassava chips show that the Page and Midilli *et al.* models satisfactorily described the drying behavior of cassava chips in all drying compartments. This is also the best fit model obtained by De Vera *et al.* [48] in the drying kinetics study of purple yam. The general form of Page and Midilli *et al.* [38] models are shown in Equations (3) and (4) respectively:

Table 3: Summary of the drying kinetic modeling of common tubers

Tuber Sample	Best Fit Model	Ref.
Potato	Diffusion model	[15], [45]
	Midilli–Kucuk model	[6]
	Page model	[32]
	Henderson and Pabis Model	[46]
Sweet potato	Page and Modified Page model	[33]
	Diffusion model	[14]
	Wang and Singh model	[41]
Yam	Midilli *et al.*, Model	[34], [48]
	Wang and Singh Model	[22]
	Weibull model	[23]
	Diffusion model	[12]
	Page and Modified Page model	[21]
Cassava	Diffusion model	[25], [26]
	Logarithmic model	[36]
	Henderson and Pabis Model	[37]
	Page model and Middilli Model	[10], [38]

$$MR = exp(-kt^n) \tag{3}$$

$$MR = aexp(-kt^n) + bt \tag{4}$$

where k is the drying rate constant and the moisture ratio MR is calculated using Equation (5). In Equation (5), M is the instantaneous moisture content of the product, M_o is the initial moisture content of the product, M_e is the equilibrium moisture and,

$$MR = \frac{M - M_e}{M_o - M_e} \tag{5}$$

A similar drying rate model was reported in the study conducted by Harish *et al.* [47] in the microwave drying kinetics of elephant foot yam and by Naderinezhad *et al.* [6] in the mathematical modeling of drying of potato slices. The general equation of the modified Page model was shown in Equation (6).

$$MR = aexp(-(kt)^n) \tag{6}$$

The Henderson and Pabis model equation was reported in the works conducted by Song *et al.* [46] in the vacuum microwave drying of potato slices and by Blaise *et al.* [37] in the mathematical modeling of thin-layer drying of cassava. The general equation of the Henderson and Pabis model was shown in Equation (7).

$$MR = aexp(-kt) + c \tag{7}$$

The Wang and Singh model equation as shown in Equation (8) was reported in the study conducted by Souza *et al.* [41] for the drying kinetics of sliced pulp of biofortified sweet potato.

$$MR = 1 + at + bt^2 \tag{8}$$

where a and b are constants to be determined experimentally.

The Logarithmic model equation as shown in Equation (9) was reported by Sanni and Odukogbe [36] in the mathematical modeling of thin-layer drying kinetics of cassava.

$$MR = aexp(-kt) + c \tag{9}$$

It is known that an optimally design drying process denotes minimum thermal energy usage during drying operation. For example, a heat loss analysis was conducted by Jitwiriya *et al.* [49] of a continuous drying oven with outside conveyor chain. They reported that the existing design creates heat waste by the absorption of heat energy inside the oven and releasing it to the outside. They reported a 23.1 % heat loss reduction with the incorporation of the new design setting all the drying paraters constant constant.

Establishing an optimally-designed drying process is highly influenced by an obtained drying rate best fit model equation. Interestingly, all tuber types such as potato, sweet potato, yam and cassava exhibit the Page model as the suitable drying rate best fit model equation. Page model has been the widely applied empirical model equation in the study of water migration in the drying of tuber. One possible reason is that Page model has been known to be successful in fitting the diffusion phenomena. Also, Page model compensate the deficiency of the exponential model by introducing the term n in the empirical equation [50].

5 Conclusions

The drying operations for common tubers is primarily influenced by the different drying parameters. These include the following; temperature, velocity of heating air medium, sample pretreatment (physical or chemical), and the initial physico-chemical properties of the sample. The increase in the temperature of the heating air medium result in a decrease in the drying time, and an increase in the drying rate. This is due to the higher mass flux of the water molecules from the inner section of the raw sample to the surface. This is followed by the rapid evaporation from the surface to the bulk air. The same results are reported when considering the effect of the velocity of the heating air medium. The initial physico-chemical properties like geometrical shape and initial moisture content also significantly affect the drying rate. These allow better design consideration and affect the mode of drying operations of common tubers. The incorporation of physical and chemical pretreatment methods enhances the drying time and improves the dried product quality. Also, among the models presented related to the drying kinetic study of tuber, it is found out that Page model is the common best fit model of all. Finally, the proper understanding of the role of the process parameters, pretreatment method, and appropriate kinetic model equations provide the basis for design consideration. This is helpful in establishing a highly-efficient drying apparatus in industrial settings.

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