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# Comparison of single and double-stage drying methods for processing tropical foods: a case study with banana and ginger

N. N. IDUN-ACQUAH, P. T. AKONOR*, L. C. BAFFOUR, D. MENSAH, P-N. T. JOHNSON
*(N.N.I-A., P.T.A., L.C.B. & D.M.: Council for Scientific and Industrial Research- Food Research Institute, Box M.20, Accra; P-N.T.J.: Department of Agro-processing Technology and Food Biosciences, CSIR-College of Science and Technology, Box M.20, Accra, Ghana)*
**Corresponding author papatoah@gmail.com*

**ABSTRACT**

In this study, the drying behaviours of banana and ginger under single-stage and double-stage hot-air convective drying were compared. Banana and ginger slices were blanched before drying at 40°C, 50°C or 60°C in the single-stage drying method. In the double-stage drying, samples were dried at 70°C during the first hour and then at 40°C, 50°C or 60°C till the end. Moisture content, colour and shrinkage were measured by standard methods. The drying data were fitted to six drying models using non-linear regression. A comparable drying rate of 0.0052 g water/g sample.min was recorded in banana dried at 60°C in both single- and double-stage methods. At 40°C and 50°C, however, drying rates were higher in double-stage than single-stage. For ginger, higher drying rates occurred at all temperatures in the single-stage compared to the double-stage mode. Midilli et al. and Page's models best described the drying behavior of both banana and ginger under both drying modes. The moisture diffusivity ranged between $1.52 – 3.07 \times 10^{-10}$ for banana and $1.27 – 2.54 \times 10^{-10}$ for ginger. Considering the changes that occurred after drying, the single-stage method is more appropriate for drying these banana and ginger.

**Keywords:** Single-stage; double-stage; drying kinetics; diffusivity; banana; ginger
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## Introduction

The processing of most tropical food crops into shelf-stable products has from antiquity been done mainly by drying. Drying ensures that the water activity of the resulting products are low enough to prevent the proliferation of spoilage microorganisms as well as considerably slow down the rates of enzyme activity and adverse biochemical reactions (Wu *et al*., 2007). Drying involves removal of water from an agricultural produce in a solid, semisolid or liquid state to produce a solid product by thermally induced phase changes (Mujumdar, 2001). It is an essential process in preserving agricultural produce, which enhances the storability, transportability, nutritional value retention, flavor and texture of agricultural food products (Wankhade *et al.,* 2014).

Drying of agricultural produce is typically done in a single-stage, which involves the use of a single drying temperature throughout the drying process. Even though hot-air convective drying has always been considered as the easiest and cheapest method of drying agricultural produce, the resulting products usually have adverse quality properties. Guine (2018) and Mohammadi *et al.* (2020) have summarized a number of these defects, which include excessive shrinkage, discoloration and loss of nutrients, and emphasized that this method of drying can be problematic for thermally sensitive materials such as fruits and vegetables.

The key causes of these defects are related to the nature of the mass transport properties of the drying air; the level of hot-air temperature and speed of hot-air flow around the drying food. Air-drying typically has two phases; an initial constant-rate and later falling-rate periods. During the constant-rate period, moisture on the surface is rapidly transported away from the food by the hot drying air, whilst during the falling-rate period moisture is removed slowly by diffusion. If the rate of the constant rate period is not fast enough, shrinkage occurs at the surface and block further outflow of moisture from the interior of the food; a phenomenon known as case-hardening (Mahiuddin *et al.*, 2018; Gulati & Datta, 2015). This will not only delay the drying process, but also allow the water activity of the drying food to reach an optimal level for enzymatic browning to take place as well as cause excessive shrinkage because of tendency of the intercellular tissues to close up (Maltini *et al.*, 2003; Mahiuddin *et al*., 2018).

To solve this problem of thermally sensitive agriculture produce, several workers have suggested the use of double-stage or multi-stage drying (Chong *et al*., 2014; Zhu *et al*., 2016). Typically, in multistage drying, an initial higher temperature is used for the short constant-rate period, followed by a relatively lower temperature during the long falling-rate period (Zhu *et al*., 2016). It may also involve the use of two or more different drying methods (Buchholz *et al*., 2021). Munde *et al.* (1988) have also explained that multistage approach of drying reduces drying time as compared to the single-stage approach.

To adequately understand the mass transport behavior during multi-stage drying of fruits and vegetables, it is important to study and apply mathematical models to drying data that will be generated. This is because the application of mathematical models in food processing helps to predict processes and equipment design. In the area of drying, many thin layer models have been proposed to describe and accurately predict drying of potatoes (Akpinar *et al*., 2003), onions (Revaskar *et al.,* 2014), okra (Doymaz, 2005), garlic and papaya (Fernando *et al*., 2008), mangoes (Dissa *et al*., 2008) and pineapples (Rani & Tripathy, 2020). These are particularly useful in understanding drying behavior, optimizing drying conditions necessary to enhance product quality, increase efficiency and regulate energy consumption (Belghith *et al*., 2016). The application of multistage drying in processing tropical foods such as banana and ginger, and its influence on their drying kinetics and quality properties remains an underexplored area.

Both banana and ginger are important tropical foods. Bananas contain vitamins A, C and $B_6$ (Robinson & Sauco, 2010). They also contain carbohydrates, fiber and polyphenols with antioxidant capacity, such as flavonoids, anthocyanins and tannins (Pérez *et al*., 2011). Bananas are cholesterol free and low in sodium (Robinson & Sauco, 2010). They are easily digestible, have appreciable mineral content and are a rich source of energy (Ganesapillai *et al.,* 2011). Ginger contains oleoresin, starch, protein, mineral matters, fibers, gums, and carbohydrates, used in ayurvedic medicines (Sansaniwal *et al.,* 2015).

Previous studies involving either banana or ginger mainly focused on single-stage convective, microwave or infrared drying kinetics of these food products. For instance, Dandamrongrak *et al.* (2002) found the two-term exponential model to best describe the drying behavior of banana pretreated by either chilling, blanching and or freezing, using heat pump drying at 50°C. Correa *et al.* (2019) found that the modified Henderson and Pabis model could adequately describe its infrared drying characteristics of ginger slices. Thuwapanichayanan *et al.* (2011) showed that the convective drying of banana slices between 70°C and 100°C was characterized by two falling rate periods and effective diffusivity influenced by moisture content at these falling rate periods. The aim of this study was therefore to compare the effect of single-stage and double-stage drying on the drying behavior and some quality properties of banana and ginger.

## Materials and Methods

Medium-sized green banana (*Musa spp*) var. Cavendish and large-sized ginger (*Zingiber officinale)* var. Chinese, at a fully matured stage were purchased from a local market in Accra. The banana and ginger were kept at room temperature of 28±1°C overnight at the Food Research Laboratory of the CSIR-Food Research Institute in Accra.

*Processing of Raw Materials*

Banana: The banana samples were washed, hand-peeled and manually cut transversely into small slices of 5 mm thickness. The banana slices were soaked in a 10% citric acid solution for 10 minutes, and blanched in a boiling water bath for 10 minutes.

Ginger: The ginger rhizomes were washed and hand-peeled using a stainless steel knife. Peeling was carried out gently to avoid damaging the cells immediately below the skin because they contain much of the volatile oils upon which the aroma of the best qualities ginger depends. Thereafter, the peeled ginger samples were washed to get rid of all foreign material before cutting transversely into slices of 5 mm thickness. Ginger slices were blanched in a boiling water bath for 10 minutes before drying.

Drying: The banana and ginger slices were each spread in a single layer on drying rectangular shallow trays (37.3 cm x 30.7 cm x 3.2 cm) and finally placed in a forced draft oven (Gallenkamp, UK) after steady conditions were achieved. Samples of banana (200 g) or ginger (200 g) were dried using the single-stage and double-stage methods. In the single-stage method, only one temperature setting (40°C, 50°C or 60°C) was used throughout the entire drying period. In the double-stage method, however, two temperature settings were used. During the first hour, samples were dried at 70°C. Thereafter, the temperature was reduced to 40°C, 50°C or 60°C for the rest of the drying period. Moisture loss during drying was monitored by measuring the weight lost in samples at 30 min intervals, until a constant weight was attained and drying stopped. The dried banana and ginger samples were allowed to cool to room temperature, packed into transparent polypropylene pouches and sealed air tight.

*Analytical methods*

Moisture: At the beginning and the ending of drying, sample moisture content was determined using AOAC method 930.15 (AOAC, 2005).

Colour: Colour determination of drying samples was by measuring the L, a, b parameters, using a colour meter (Minolta 410, Osaka Japan). This determination was done before drying, during drying and after drying. The extent of browning during drying, Browning Index (*BI*), was calculated using the formula (Kasim & Kasim, 2014),

$$BI = \frac{[100(x - 0.31)]}{0.17}, \tag{1}$$

$$x = \frac{a + 1.75L}{5.645L + a - 3.012b} \quad (2)$$

where L, a, b respectively indicate lightness or darkness, redness or greenness, yellowness or blueness of sample from the equations above (Kasim & Kasim, 2014).

Shrinkage: Area shrinkage was determined by following the method of Akonor & Tortoe (2014). Shrinkage was assumed to occur in only one dimension (surface area), considering the thin nature of the slices used. The dimensions (diameter) of fresh and dried samples were measured using a digital Vernier caliper (Mitutoyo, Japan) with a precision of 0.01 mm. Dimensions were measured at several places for fresh or dried banana and ginger slices to calculate a mean surface area for samples. The extent of shrinkage was expressed as percentage shrinkage and calculated using the formula,

$$\%\,Shrinkage = \frac{A_0 - A_d}{A_0}\ x\ 100 \quad (3)$$

where $A_0$ and $A_d$ are the respective surface area of banana or ginger slice before and after drying.

Model fitting: Moisture ratio (MR) of banana and ginger slices was calculated as follows;

$$MR = M_t - M_e/M_o - M \quad (4)$$

where $M_t$ is the moisture content after time t, $M_e$ is the equilibrium moisture content and $M_o$ is the initial moisture content. Since $M_e$ is very small compared to $M_o$ and $M_t$, it is neglected (Goyal *et al.*, 2007) and equation (4) is simplified as

$$MR = M_t/M_o \quad (5)$$

Experimental drying data were fitted to six drying models (Table 1) commonly used to describe thin layer drying kinetics, using non-linear regression (Statgraphics Centurion XVI, Statgraphics Technologies, Inc). The criterion for selecting the best model was the coefficient of determination ($R^2$), while Root Mean Square Error (RMSE) was used to determine the adequacy of a model in fitting the drying data. High $R^2$ and low RMSE corresponds to a model with better fit.

TABLE 1
*Thin layer drying models for fitting experimental drying data*

| **Model** | **Equation** | **References** |
|---|---|---|
| Lewis | MR = *exp (-kt)* | Akpinar *et al.* (2003) |
| Page | MR = *exp (-kt$^y$)* | Cai & Chen (2008) |
| Henderson and Pabis | MR = a *exp (-kt)* | Henderson & Pabis (1961) |
| Midilli et al. | MR = a *exp (-kt$^y$)+bt* | Midilli *et al.* (2002) |
| Logarithmic | MR = a *exp (-kt)+c* | Doymaz & Akgun (2009) |
| Diffusion | MR = a *exp (-kt) + (1 – a) exp(-kbt)* | Demir *et al.* (2007) |

*Effective moisture diffusivity*

Effective moisture diffusivity ($D_{eff}$) describes the rate of moisture movement during drying in which diffusion is assumed to be the main transport mechanism. It is related to MR by,

$$\ln MR = \ln (8/\pi^2) - \pi^2 D_{eff} t/4L^2 \quad (6)$$

where t is the drying time (s) and L is the half thickness of a slice (assuming a slab geometry) $D_{eff}$ ($m^2/s$) was derived from the slope (K) of a plot of lnMR against time, and

$$K = \pi^2 D_{eff}/4L^2 \quad (7)$$

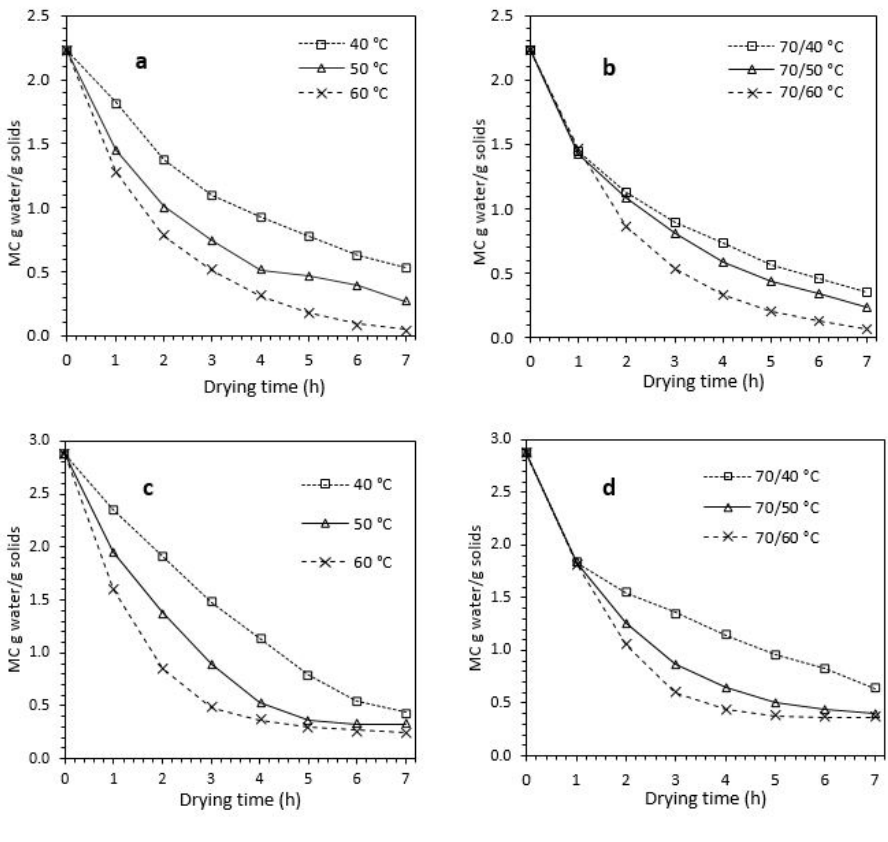
*Data analyses*

Data from the physical quality measurements was compared using ANOVA at 95% significant level (XLSTAT, 2014).

## Results and Discussion

*Variation in moisture ratio during drying*

Generally, the rate of drying and moisture removal depend on product characteristics and operating conditions. The drying profile of the two products showed a consistent reduction in moisture content with increasing drying time (Fig. 1), and this represents the characteristic drying behavior of food materials with porous structures. Temperature, as one of the main factors that affect the drying kinetics of many products (Fernando *et al*., 2008), clearly influenced the moisture content of both banana and ginger throughout the drying period, using the different drying methods. Higher drying temperatures resulted in faster rate of moisture loss (steeper curve), and lower final moisture content in each commodity.




higher

Fig. 1: Drying profile of banana single-stage (a) and double-stage (b); and ginger single-stage (c) and double-stage (d) slices

reduction in moisture occurred during the first hour of drying in the double-stage drying mode because of higher drying temperature of 70°C, compared to 40°C, 50°C in the single-stage mode. Nevertheless, the difference in moisture levels of samples dried at 60°C using the single-stage method was not vastly different from 60°C involving the double-stage drying method. The high initial drying temperature in the double-stage drying method may also explain why drying rates were apparently higher compared to the single-stage drying.

*Drying rate*

The drying rate continuously declined over the entire drying period, as moisture levels reduced (Fig. 2); an indication that the drying took place in the falling rate period (Earle & Earle, 2004; Dhali & Datta, 2019; Akpinar *et al*., 2003). The decrease in drying rate is explained by a reduction in moisture migration from the core of the food material and evaporation rate at the food's surface when the moisture content decreases during drying. During the first hour, drying rates were slightly higher for both banana and ginger dried at 60°C in the single-stage than in the multi-stage, suggesting that temperature alone did not control the drying rate. For banana, a rate of 0.0158 and 0.0130 g water/g dry sample.min dry samples were respectively recorded in the single- and double-stage drying, whiles 0.0212 and 0.0175 g water/g dry sample.min were correspondingly observed for ginger in the two drying modes. A possible explanation is that, in the multistage, the initial temperature of 70°C causes a steep moisture gradient through the product. This will lead to the external surface of the product having low moisture which may induce a rubber glass transition and formation of a shell that impedes moisture diffusion (Mayor & Sereno, 2004).

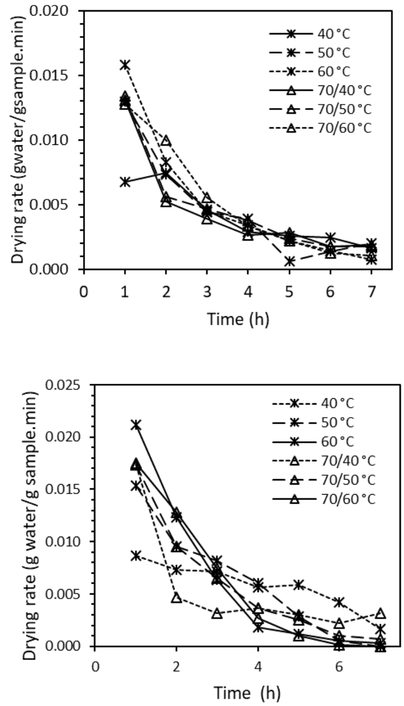



Fig. 2: Drying rate of banana (a) and ginger (b) using single-stage and double-stage drying methods

At 40°C and 50°C, higher drying rates were initially recorded in double- than single-stage drying. This implies that the high starting temperature of 70°C, was obviously the most influential determinant of drying rate at lower temperatures. Beyond the first hour, the impact of temperature is clearly manifested in both drying techniques, with higher drying rates occurring at higher drying temperatures. In the double- stage drying, there was a steep reduction in drying rate after the first hour, especially when the temperature was reduced to 50°C or 40°C. According to Nguyen & Price (2007), falling rate drying is controlled by concentration gradient, a factor which is temperature dependent, as well as the nature of the macro-structure of the food material (Palamba *et al*., 2018). Similar trends in drying rate have been reported by Akpinar *et al.* (2003) for potato slices, and Dinani & Havet (2015) for mushrooms.

TABLE 2a

*Model fitting criteria for the drying models and parameters for drying banana in different modes*

| **Model** | **Temperature (°C)** | $R^2$ | | **Reduced chi square ($\chi^2$)** | | **RMSE** | |
|---|---|---|---|---|---|---|---|
| | | *SS* | DS | SS | DS | SS | DS |
| | 40 | 0.9773 | 0.9716 | 0.00184 | 0.00221 | 0.0429 | 0.0470 |
| Lewis | 50 | 0.9805 | 0.9899 | 0.00172 | 0.00092 | 0.0415 | 0.0303 |
| | 60 | 0.9986 | 0.9987 | 0.00016 | 0.00016 | 0.0125 | 0.0126 |
| | 40 | 0.9759 | 0.9759 | 0.00195 | 0.00187 | 0.0408 | 0.0400 |
| Henderson and Pabis | 50 | 0.9806 | 0.9909 | 0.00171 | 0.00083 | 0.0383 | 0.0266 |
| | 60 | 0.9985 | 0.9986 | 0.00017 | 0.00016 | 0.0120 | 0.0117 |
| | 40 | 0.9749 | 0.9982 | 0.00203 | 0.00014 | 0.0418 | 0.0111 |
| Page | 50 | 0.9950 | 0.9982 | 0.00045 | 0.00016 | 0.0179 | 0.0118 |
| | 60 | 0.9991 | 0.9996 | 0.00010 | 0.00005 | 0.0092 | 0.0067 |
| | 40 | 0.9775 | 0.9998 | 0.00182 | 0.00002 | 0.0323 | 0.0033 |
| Midilli et al. | 50 | 0.9958 | 0.9990 | 0.00037 | 0.00009 | 0.0160 | 0.0072 |
| | 60 | 0.9998 | 0.9995 | 0.00003 | 0.00007 | 0.0038 | 0.0061 |
| | 40 | 0.9722 | 0.9872 | 0.00225 | 0.00099 | 0.0401 | 0.0266 |
| Logarithmic | 50 | 0.9953 | 0.9933 | 0.00042 | 0.00061 | 0.0173 | 0.0209 |
| | 60 | 0.9982 | 0.9988 | 0.00020 | 0.00014 | 0.0120 | 0.0101 |
| | 40 | 0.9682 | 0.9602 | 0.00257 | 0.00309 | 0.0429 | 0.0470 |
| Diffusion | 50 | 0.9728 | 0.9857 | 0.00241 | 0.00129 | 0.0415 | 0.0303 |
| | 60 | 0.9981 | 0.9981 | 0.00022 | 0.00022 | 0.0125 | 0.0126 |

SS – single-stage, DS – double-stage

Non-linear regression showed $R^2 > 0.9$ in all cases, suggesting that the selected thin layer drying models could adequately describe the experimental data for banana (Table 2a) and ginger (Table 2b). That notwithstanding, the Midilli et al. model was the best model to describe the single-stage drying of banana from 40°C to 60°C, with $R^2$ ranging between 0.9775 to 0.9998. Similarly, this model was the most useful in describing double-stage drying at lower drying temperatures of 40°C and 50°C. Page's model best fits the double-stage drying data at 60°C ($R^2$ – 0.9996, $\chi^2$ – 0.00005 and RMSE – 0.0067). The case of ginger was slightly different. Here, irrespective of mode or temperature used, Midilli et al. model was the best to fit all the experimental data. Thus, under the conditions provided in the single-stage and double-stage drying methods, these two models well represented the thin layer drying behaviour of both banana and ginger slices. Midilli et al. model has been found in previous studies, to best describe the thin layer drying characteristics of banana (Ganesapillai *et al*., 2011) and mushrooms (Guo *et al.*, 2014).

TABLE 2b

*Model fitting criteria for the drying models and parameters for drying ginger in different modes*

| Model | Temperature | $R^2$ | | Reduced chi square ($\chi^2$) | | RMSE | |
|---|---|---|---|---|---|---|---|
| | | SS | DS | SS | DS | SS | DS |
| Lewis | 40 | 0.9870 | 0.9576 | 0.00122 | 0.00270 | 0.0350 | 0.0520 |
| | 50 | 0.9969 | 0.9739 | 0.00034 | 0.00230 | 0.0184 | 0.0480 |
| | 60 | 0.9702 | 0.9775 | 0.00299 | 0.00227 | 0.0547 | 0.0477 |
| Henderson and Pabis | 40 | 0.9877 | 0.9669 | 0.00115 | 0.00211 | 0.0314 | 0.0425 |
| | 50 | 0.9964 | 0.9746 | 0.00039 | 0.00224 | 0.0182 | 0.0438 |
| | 60 | 0.9660 | 0.9741 | 0.00341 | 0.00262 | 0.0541 | 0.0474 |
| Page | 40 | 0.9980 | 0.9962 | 0.00019 | 0.00024 | 0.0127 | 0.0143 |
| | 50 | 0.9968 | 0.9978 | 0.00035 | 0.00020 | 0.0174 | 0.0132 |
| | 60 | 0.9813 | 0.9808 | 0.00188 | 0.00194 | 0.0401 | 0.0408 |
| Midilli et al. | 40 | 0.9975 | 0.9991 | 0.00023 | 0.00006 | 0.0115 | 0.0058 |
| | 50 | 0.9967 | 0.9986 | 0.00036 | 0.00013 | 0.0144 | 0.0085 |
| | 60 | 0.9995 | 0.9994 | 0.00005 | 0.00005 | 0.0055 | 0.0057 |
| Logarithmic | 40 | 0.9970 | 0.9812 | 0.00028 | 0.00120 | 0.0142 | 0.0292 |
| | 50 | 0.9957 | 0.9969 | 0.00047 | 0.00028 | 0.0182 | 0.0141 |
| | 60 | 0.9956 | 0.9921 | 0.00044 | 0.00079 | 0.0177 | 0.0238 |
| Diffusion | 40 | 0.9818 | 0.9407 | 0.00171 | 0.00378 | 0.0350 | 0.0520 |
| | 50 | 0.9956 | 0.9635 | 0.00047 | 0.00322 | 0.0184 | 0.0480 |
| | 60 | 0.9583 | 0.9685 | 0.00419 | 0.00318 | 0.0547 | 0.0477 |

SS – single-stage, DS – double-stage

*Effective moisture diffusivity*

In food and other agro-based products, diffusion is the predominant moisture migration mechanism in drying of fruits and vegetables, and its rate is described by the Effective moisture diffusivity ($D_{eff}$). The $D_{eff}$ is a function of moisture content and temperature (Prachayawarakorn *et al*., 2008). In this study, $D_{eff}$ values ranged between 1.5 – 5.1 × $10^{-10}$ $m^2/s$ and 1.3 – 2.5 × $10^{-10}$ $m^2/s$ correspondingly for banana (Table 3a) and ginger (Table 3b). Generally, higher moisture diffusivity were recorded at higher drying temperature, translating into higher moisture loss over the drying period, as indicated in Fig. 1. This is because higher temperatures increase the movement of water from the inner to the outer surface, and also enhances surface evaporation (Thuwapanichayanan *et al*., 2011). At the onset of drying, the products heats up and there is moisture loss through diffusion, and this gradually transitions into vapour.

TABLE 3a

*Moisture diffusivity in banana using single-stage and double-stage drying methods*

| Drying mode | Temperature (°C) | $D_{eff}$ (m²/s) | $R^2$ |
|---|---|---|---|
| Single-stage | 40 | $1.52 \times 10^{-10}$ | 0.9941 |
| | 50 | $2.03 \times 10^{-10}$ | 0.9753 |
| | 60 | $3.07 \times 10^{-10}$ | 0.9951 |
| Double-stage | 70/40 | $1.77 \times 10^{-10}$ | 0.9978 |
| | 70/50 | $2.28 \times 10^{-10}$ | 0.9968 |
| | 70/60 | $2.54 \times 10^{-10}$ | 0.9898 |

TABLE 3b

*Moisture diffusivity in ginger using single-stage and double-stage drying methods*

| Drying mode | Temperature (°C) | $D_{eff}$ (m²/s) | $R^2$ |
|---|---|---|---|
| Single-stage | 40 | $2.03 \times 10^{-10}$ | 0.8293 |
| | 50 | $2.28 \times 10^{-10}$ | 0.9765 |
| | 60 | $2.54 \times 10^{-10}$ | 0.9883 |
| Double-stage | 70/40 | $1.27 \times 10^{-10}$ | 0.8782 |
| | 70/50 | $2.03 \times 10^{-10}$ | 0.9570 |
| | 70/60 | $2.28 \times 10^{-10}$ | 0.9845 |

Similar trend of increasing $D_{eff}$ with increasing temperature have been previously reported for two varieties of banana dried between 40°C and 70°C by (Demirel & Turhan, 2013), for ginger slices (Correa *et al*., 2019), for onion slices (Revaskar *et al*., 2014), and for potato slices (Akpinar *et al*., 2003). In banana, higher $D_{eff}$ were recorded when lower temperatures (40°C and 50°C) were used in the double-stage drying mode. However, at 60°C, a faster rate of moisture removal occurred in the single-stage mode, similar to the trend in drying rates observed in this study. A plausible explanation for this is that higher temperatures induced extensive capillary collapse, obstructing the diffusion of water from the inner to the outer surface of the products. A different trend was observed in ginger, where higher $D_{eff}$ were recorded for all the temperatures during the single-stage drying mode. $D_{eff}$ obtained in this study for the two products under the different drying modes, were consistent with the range of $10^{-12}$ – $10^{-8}$ reported by Labuza & Altunaker (2007) for most food products. The values were also comparable to $10^{-11}$ to $10^{-10}$ m²/s obtained in earlier studies by Thuwapanichayanan *et al.* (2011) for banana dried at 70°C – 100°C, but lower than $9.4 \times 10^{-7}$ to $1.2 \times 10^{-6}$ m²/s for controlled humidity-convective drying of banana (Sarpong *et al*., 2018).

*Effect of the single- and double-stage drying on the colour and shrinkage of banana and ginger*

Colour and extent of shrinkage are two key physical characteristics that consumers normally use to visibly judge the quality of dried food products. Table 4 shows that there was slight browning occurring in both products during the drying process, even though they were initially blanched in boiling water before drying. Additionally, even though there was browning in both single- and double-stage drying of banana as indicated by increasing BI value, the effect was more pronounced during the double-stage drying.

TABLE 4

*Colour indices of dried banana and ginger slices*

| Drying mode | Drying temperature (°C) | BI | | Hue |
|---|---|---|---|---|
| | | Banana | Ginger | Banana |
| Single stage | 40 | 7.02±1.35[a] | 4.30±0.41[a] | 125.60±2.63[c] |
| | 50 | 11.68±0.14[b] | 5.440.31[a] | 116.89±1.32[a] |
| | 60 | 12.95±0.68[c] | 7.6±0.57[b] | 115.37±0.82[a] |
| Double stage | 70/40 | 7.95±0.42[a] | 7.89±0.98[b] | 124.50±1.19[c] |
| | 70/50 | 11.53±1.11[b] | 8.13±0.3[b] | 119.57±1.59[b] |
| | 70/60 | 13.01±0.22[c] | 11.53±66[c] | 117.32±1.02[a] |

At the lowest drying temperature of 40°C, however, BI was higher in the double- than in the single-stage drying. Korbel *et al*. (2013) have explained that both water activity and temperature play major roles in non-enzymatic browning during the drying of fruits. Therefore, the higher BI noted here could be attributed to the fact that the water activity of the drying sample and the initially high temperature (70°C), at this stage, may have reached optimal conditions for the browning reactions in the banana slices. This explanation also applies to the ginger, in which a similar trend was observed. A gradual decrease in the hue colour of the final dried product occurred when drying temperature increased from 40°C to 60°C. That notwithstanding, the hue of the dried slices at 50°C were not notably different ($p > 0.05$) from those dried at 60°C.

The reduction in the hue of banana slices depicts a drift towards "yellowness" on the CIELAB colour space, and reflects the darkening of banana slices as drying temperature increased. Visually, the dried banana appeared slightly brownish-yellow, indicating an extent of discoloration at the end of the drying period. Discoloration of banana slices increased with increasing temperature because temperature enhances browning reactions during drying. These reactions are caused by enzyme activity, oxidation of polyphenols by polyphenol oxidase or non-enzymatic pathway in which reducing sugars act as a substrate and low molecular weight acids, provide the necessary reaction conditions. The extent of browning reactions and pigment degradation is also influenced by sugar content, temperature and exposure time. Related discoloration of banana during drying, and an increase in browning with increasing temperature have been reported elsewhere (Demirel & Turhan, 2003).

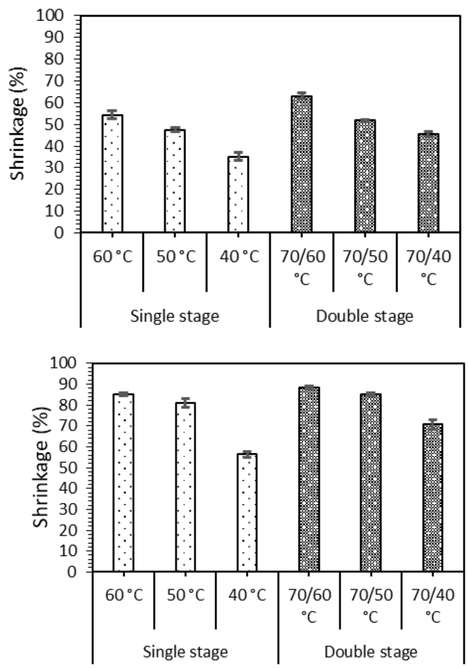



Fig. 3: Extent of shrinkage during single-stage and double-stage drying of (a) banana slices, (b) ginger slices

Although banana normally shrinks between 43% – 47% during drying according to Queiroz & Nebra (2001), a much wider range, 35% – 56%, was recorded in this study (Fig. 3a). These disparities could be ascribed to differences in variety of banana, raw material and drying conditions used in the previous study. In agreement with the belief that considerable shrinkage occurs during the drying of ginger (Yang *et al*., 2006), shrinkage in ginger slices was in a range of 56% – 88% (Figure 2b). Ginger shrinks extensively when dried because it has a fibrous texture with poor elasticity (Li & Sun, 2020), which easily collapses when there is a pressure imbalance between its inner and external parts because of water loss during drying. In both banana and ginger, shrinkage increased with increasing temperature for both single- and double-stage drying methods.

For instance, shrinkage of 35% was recorded in banana dried at 40°C, while 53% was recorded for the same crop dried at 60°C. This was expected because increasing drying temperature causes rapid moisture loss which induces greater stress in the cellular structure of the food material, resulting in cell collapse and dimension reduction (Mahiuddin *et al*., 2018). Below 50°C, intercellular moisture migration is slow, and occurs only through microcapillary migration, leading to low deformation (Halder *et al*., 2011). Also, shrinkage is proportional to the volume of water removed, therefore, products dried at 60°C, which evidently had lower final moisture content (Fig. 1), shrunk more than those dried at 40°C, with a higher final moisture content.

Shrinkage directly affects heat and mass transfer during drying, and by extension, the quality of the final dry product (Aprajeeta *et al*., 2015). It may induce surface deformation and cracking due to internal tension resulting from non-uniform contraction in both radial and axial directions during moisture loss (Hernandez-Diaz *et al*., 2008). It also influences rehydration capacity by collapsing cell structure and capillaries, leading to the formation of a dense structure which restrains rehydration ability (Mayor & Sereno, 2004). In addition to shrinkage, case hardening also negatively affects the appearance and other sensory attributes. The trends observed in this study compare well with findings of previous studies in which increasing temperature correspondingly increased shrinkage in Rani & Tripathy (2018) who reported a 79.3% axial shrinkage in pineapple slice dried at 70°C.

## Conclusion and Recommendation

This study showed variations in the drying behavior of banana and ginger using the single-stage or the double-stage drying method. The drying rate declined with increasing temperature and drying time in both drying methods. Nevertheless, the drying rates seemed to be product dependent. In banana, the mean drying rates were comparable at 60°C in both single- and double-stages, but higher in double- stage drying at 50°C (0.0048 vs 0.0048 g water/g sample.min) and 40°C (0.0045, 0.0040 g water/g sample.min), whereas higher drying rates of 0.0058, 0.0060, 0.0062 g water/g sample.min were recorded in the single-stage drying of ginger at 40°C, 50°C, 60°C, compared to 0.0053, 0.0059 and 0.0060 g water/g sample.min using the double-stage method.

Shrinkage increased with increasing temperature, but was higher in double-stage compared to the single-stage drying method. Midilli et al. and Page's models best described the single-stage and double-stage drying behaviors of both products. Moisture diffusivity was higher, $3.07 \times 10^{-10}$, in single-stage drying of banana 60°C compared to $2.54 \times 10^{-10}$ using the double-stage method, but this was higher at 40°C and 50°C when the double-stage method was used. However, in ginger, higher diffusivity (2.03 – 2.54 × $10^{-10}$) were encountered in the single-stage compared to double-stage ginger (1.27 – 2.28 × $10^{-10}$). Product discoloration and shrinkage were higher in double-stage drying than single-stage drying of both banana and ginger. All these lead to the conclusion that, for banana and ginger, single-stage drying is more preferable than double-stage drying

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