Determination of effective moisture diffusivity of banana using Thermogravimetric analysis

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Abstract

Drying has been extensively used as a food preservation procedure. The longer life attained by drying is however accompanied by huge energy consumption and deterioration of quality. Moisture diffusivity is an important factor that is considered essential to understand for design, analysis, and optimization of drying processes for food and other materials. Without an accurate value of moisture diffusivity, drying kinetics, energy consumption, quality attributes such as shrinkage, texture, and microstructure cannot be predicted properly. However, moisture diffusivities differ due to variation of composition and microstructure of foodstuff and drying variables. For a particular food, it changes with many factors including moisture content, water holding capacity, process variables and physiochemical attributes of food. Published information on moisture diffusivities of banana is inadequate and sometimes inconsistent due to lack of precise repeatable analysis techniques. In this work, the effective moisture diffusivity of banana was determined by Thermogravimetric Analysis (TGA), which ensures precise measurements and reproduction of experiments. A TGA Q500 V20.13 Build 39 was deployed to obtain the drying curve of the food material. It was found that effective moisture diffusivity ranged from $6.63 \times 10^{-10}$ to $1.03 \times 10^{-9}$ and $1.34 \times 10^{-10}$ to $6.60 \times 10^{-10}$ for isothermal at 70°C and non-isothermal process respectively. These values are consistent with the value of moisture diffusivity found in the literature.

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1. Introduction

The issue of dried food quality has recently received considerable attention. Fruits and vegetables are important sources of essential dietary nutrients such as vitamins, minerals and fiber. Since the moisture content of fresh fruits and vegetables is generally more than 80%, they are classified as highly perishable commodities [1].

Nomenclature

| Symbol | Description |
|--------|-------------|
| MR     | Moisture ratio |
| M₀     | Initial moisture content, kg/kg db |
| Mₜ     | Moisture content at time t, kg/kg db |
| Mₑ     | Equilibrium moisture content, kg/kg db |
| Dₑff   | Effective moisture diffusivity, m²/s |
| L      | Half thickness of the sample, m |
| t      | Time, s |

Food is one of the most complex materials in natural form and the fundamental understanding of food drying has not been fully established [2]. Lack of proper processing causes considerable damage and wastage of seasonal fruits in many countries, which is estimated to be 30–40% in developing countries[3]. Drying of foodstuffs is an important and the oldest method of food processing. Many physical and chemical changes occur in foods during the drying process. The quality of dehydrated product is affected by a number of factors and is dependent on the quality of raw material, method of preparing, processing treatments and drying conditions[4]. The process of drying commonly means moisture evaporation due to simultaneous heat and mass transfer [5].

Drying rate can be separated into a constant rate period and one or more falling rate stage [6]. The sample surface contains free moisture and therefore during the first stage of drying constant drying rate is observed. In this stage vaporization of this free moisture takes place [7]. After this period, to facilitate drying, the moisture has to be diffused from the inside of the material to the surface. Therefore, from the point called critical moisture content (Mₑ), first falling stage of drying starts. Diffusion rate decreases in the falling rate drying period due to shrinkage and lower moisture gradient which result is longer drying time. Drying behavior of some biological and most food materials experience this second falling rate period.

Effective moisture diffusivity is one of the important parameters that have to be considered for analysis and optimization of dehydration process. Correct simulation of different drying processes also demands precise value of moisture diffusivity [8]. However moisture diffusivity varies due to numerous factors such as food material properties and process parameters. For a particular material, moisture distribution defers with factors like processing temperature, physical structure, moisture content and porosity [9]. Specially, anisotropy nature of plant tissue makes it more difficult to attain exactly same reproductive sample materials. Different methods have been developed in order to get insight of moisture transport within foodstuffs, such as, drying method, permeability method, sorption kinetics method, moisture profile method [10]. It is essential to maintain repetitive nature of the process in order to attain accurate moisture diffusivity. Many researchers [11, 12] have used Thermogravimetric analysis (TGA) to mathematical modeling of mass transfer, which offers high level of repeatability of drying process. In addition, TGA has a number of attractive features; it provides precise measurement of temperature, time and weight. Furthermore, it allows heating the sample at exactly set temperature, online record of the process parameters and minimal requirement of materials [12].

The objective of this work was to determine the effective moisture diffusivity of banana at isothermal condition at70°C and non-isothermal condition. TGA technique has been used to obtain drying data, and to use the slope method in order to determine moisture diffusivity.
2. Materials and method

2.1. Material

Fresh banana was bought from supermarket in Brisbane, Australia. Samples were cut at thickness of 3mm using a sharp knife. Immediately after cutting the sample, it was put into the crucible to avoid moisture loss and oxidation.

2.2. Drying Procedure

Drying experiments were performed at 70°C and non-isothermal condition with 1°C/min heating rate using a Thermogravimetric analyser (TGA Q500 V20.13 Build 39). The TGA, as shown in the schematic diagram in Fig. 1, with its infrared furnace can allow immediate set temperature and it has precise temperature control. Banana slices with 80-90 mg weight and 3mm thickness were placed into TGA crucible, and the carrying gas (nitrogen) flow was kept at 100 mL/min. All weight lost, temperature and time data recorded in a computer.

![Schematic diagram of TGA of this study.](image)

2.3. Drying behaviour and effective moisture diffusivity of banana

Drying behaviour of food material is essential to understand in order to get better prediction of quality and obtain optimum drying condition. The complex nature of food materials causes more than one internal mass transfer mechanism during the time of drying. Different mode of mass transfer may exist at the same time in a system. However one of them dominates at a certain time in the system. Drying of banana dominantly follows falling rate period. Furthermore, diffusivity is commonly used to describe drying kinetics of plant tissues (fruits and vegetables) in their falling rate stage, and the driving force of diffusion is concentration gradient. This falling rate period of drying can be modelled using Fick’s law. Fick’s second law can be expressed as:
Where, moisture ratio MR, was calculated using the following equation

\[
MR = \frac{M - M_e}{M_0 - M_e} \tag{2}
\]

It is assumed that initial moisture content is uniform in banana slabs. It is also assumed that external mass transfer resistance is negligible and moisture migration from the food material occurs in one dimension. For one directional drying in an infinite slab, Crank [13] gave an analytical solution, as given below:

\[
MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left( -\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2} \right) \tag{3}
\]

Where, \( n \) is a positive integer, \( t \) is drying time (sec), and \( L \) is sample thickness (m). Considering uniform initial moisture distribution and negligible shrinkage, Eq. (3) is suitable for determining effective moisture diffusivity. A simplified approach shown in Eq. (4) can be obtained taking only the first term of series solutions in Eq. (3). This equation could be further simplified into Eq. (5) by taking the first term of a series solution as follows [14].

\[
\ln \left( \frac{M - M_e}{M_0 - M_e} \right) = \ln \left( \frac{8}{\pi^2} \right) - \frac{\pi^2 D_{eff} t}{4L^2} \tag{4}
\]

Effective moisture diffusion could be determined from the slope \( k \) obtained from the plot of \( \ln \left( \frac{M - M_e}{M_0 - M_e} \right) \) versus time. The slope of the straight line can be expressed as follows;

\[
\text{slope} = \frac{\pi^2 D}{4L^2} = K \tag{5}
\]

Where \( L \) = the thickness of the slab, if drying occurred only on one large face. In this study, drying occurred on two faces, as slabs were placed on a mesh tray. In this case \( L = \) half thickness.

3. Results and Discussion:

Isothermal temperature at 70\(^\circ\)C was maintained throughout the drying process. As temperature gradient during drying has a noticeable influence on drying kinetics, a non-isothermal drying with 1 \(^\circ\)C/min heating rate also has been compared with the drying rate of isothermal process at 70\(^\circ\)C (Fig. 2).
Fig. 2. Change of moisture content of banana with time

It can be apparent from Fig. 2 that drying approach (isothermal or non-isothermal) significantly influences the drying process. In case of isothermal it reached equilibrium moisture content earlier than that of non-isothermal process.

Fig. 3. Effective moisture diffusivity with moisture content

Moisture diffusivity curve, as shown in Fig. 3, demonstrates that it varies with moisture content. The striking observation to emerge from the moisture diffusion data was in isothermal process confirms the second falling rate at moisture 0.3 kg/kg db, whereas for non-isothermal at the same moisture interestingly rising rate of diffusion has also been observed. This might be caused due to migration of bound water (either physically or chemically bounded) at higher temperature (136 °C). However, Effective moisture diffusivity obtained for both isothermal at 70 °C and non-isothermal process are within very close limit found in the literatures as show in Table 1.

Table 1. Effective moisture diffusivity of banana at different conditions

| Drying Process       | Temperature (°C) | Moisture diffusivity (m²/s)                  | References |
|----------------------|------------------|---------------------------------------------|------------|
| TGA (Isothermal)     | 70               | 6.63 × 10⁻¹⁰ to 1.03 × 10⁻⁹                 | This study |
| TGA (Non-isothermal) | 26-142           | 1.34 × 10⁻¹⁰ to 6.60 × 10⁻¹⁰                 | This study |
| Air drying           | 50-70            | 2.80 × 10⁻¹⁰ to 6.40 × 10⁻¹⁰                 | [15]       |
| Air drying           | 70               | 8.50 × 10⁻¹⁰ to 6.45 × 10⁻¹⁰                 | [16]       |
| Air drying           | 70               | 1.36 × 10⁻¹⁰                                 | [17]       |
| Ultrasound pre-treated | 70               | 1.29 × 10⁻¹⁰ to 1.83 × 10⁻¹⁰                 | [18]       |

4. Conclusion

The drying features of banana slabs were studied in TGA with both isothermal and non-isothermal conditions. With the precise measurement of weights and temperature, as well as immediate development of set temperature, the TGA method proved suitable for determination of effective moisture diffusivity. It was found that effective moisture diffusivity ranged from 6.63 × 10⁻¹⁰ to 1.03 × 10⁻⁹ and 1.34 × 10⁻¹⁰ to 6.60 × 10⁻¹⁰ for isothermal at 70 °C and non-isothermal process respectively. This study provides a simple but accurate method of determination of effective moisture diffusivity of plant tissue.
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