MONITORING AND MODELLING OF MOISTURE CONTENT WITH NUCLEAR MAGNETIC RESONANCE (NMR)

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ABSTRACT

MONITORING AND MODELLING OF MOISTURE CONTENT WITH NUCLEAR MAGNETIC RESONANCE (NMR)

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The aim of this study is to observe the variation of the moisture content and drying rate over time, temperature, and position. Chickpea puree, eggplant, and apple were selected for drying, and the drying experiments were performed at 50-70°C for 3 h. The moisture content of samples was measured using oven, time-domain nuclear magnetic resonance (TD-NMR), and magnetic resonance imaging (MRI) methods. The changes in moisture content and drying rate with temperature and position were monitored. The drying rate of chickpea drying was 0.34-0.44 kgH_2O/m^2h and the drying time was estimated as 440-320 min depending on the drying temperature and position. The drying rate of eggplant drying was 0.38-0.62 kgH_2O/m^2h and the drying time was estimated as 460-280 min depending on the drying temperature and position. The drying rate of apple drying was 0.65-0.99 kgH_2O/m^2h and the drying time was estimated as 420-260 min depending on the drying temperature and position. It was concluded that TD-NMR and MRI methods were effective, high-sensitive and precise in estimating moisture content during drying process.

Keywords: Moisture Content Determination,TD-NMR, MRI, Oven Method

ÖZ

NÜKLEER MANYETİK REZONANS (NMR) İLE NEM İÇERİĞİNİN İZLENMESİ VE MODELLENMESİ

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Bu çalışmanın amacı, nem içeriğinin ve kuruma hızının zamana, sıcaklığa ve konuma göre değişimini gözlemlemektir. Kurutma için nohut püresi, patlıcan ve elma seçilmiş ve kurutma deneyleri 50-70°C'de 3 saat süreyle gerçekleştirilmiştir. Numunelerin nem içeriği fırın, zaman alanlı nükleer manyetik rezonans (TD-NMR) ve manyetik rezonans görüntüleme (MRI) yöntemleri kullanılarak ölçülmüştür. Sıcaklık ve konum ile nem içeriği ve kuruma hızındaki değişiklikler izlendi. Nohut kurutmanın kuruma hızı 0.34-0.44 kgH_2O/m^2h ve kurutma sıcaklığına ve konumuna bağlı olarak kuruma süresi 440-320 dakika olarak tahmin edilmiştir. Patlıcan kurutmasının kuruma hızı 0.38-0.62 kgH_2O/m^2h ve kuruma süresi kurutma sıcaklığına ve konumuna bağlı olarak 460-280 dakika olarak tahmin edilmiştir. Elma kurutmanın kuruma hızı 0.65-0.99 kgH_2O/m^2h ve kurutma sıcaklığına ve konumuna bağlı olarak kuruma süresi 420-260 dakika olarak tahmin edilmiştir. TD-NMR ve MRI yöntemlerinin kurutma işlemi sırasında nem içeriğini tahmin etmede etkili, yüksek duyarlı ve hassas olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Nem İçeriği Belirleme, TD-NMR, MRG, Fırın Methodu

To my dear family…

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LIST OF SYMBOLS

SI=Signal Intensity

M_0=Proton Intensity

T_1= Longitudinal relaxation time

T_2= Transverse relaxation time

Tr= Repetition time

TE=Echo time

M_t =Moisture content at time t

M_e =Equilibrium moisture content

M_0 = Moisture content at initial time

R_d=Drying rate

W =Dry solid weight

M=Moisture value on a dry basis

A =Area

MAE = Mean absolute error

$RMSE$ = Root mean square error

CHAPTER 1

INTRODUCTION

People have been looking for ways to safely store their food for a longer period of time. Drying, fermentation, pasteurization, freezing and irradiation are a few of these methods. With all these methods, it is aimed to both extend the shelf life of the food and increase its microbial safety (Scariot et al., 2020).

Drying is the oldest method used to preserve food. Drying is used to reduce the growth of spoilage microorganisms and to prevent the occurrence of chemical reactions. Drying is defined as reducing the water content of raw, semi-processed or processed solid, liquid and semi-liquid foods to certain levels (Yadav & Singh, 2014). The amount of water in fresh foods varies between 90 and 70%. During drying process, this amount of water decreases to 10-20% (Mohammadhosseini et al., 2021). The drying process prevents deterioration of the product by limiting the microbial growth and enzymatic activities in products. It ensures preservation of quality such as aroma and nutritional value. Thus, the shelf life of food products is extended (Mugi & Chandramohan, 2021). In addition, since the volume of the food is reduced, it provides convenience in transportation and storage. New food products can be produced using the drying process (milk powder, whey powder, etc.).

In drying process, it is observed that the liquid is evaporated and removed from the solid with the simultaneous heat and mass transfer. During drying process, heat required for evaporation is supplied to the product and moisture of the food is evaporated and taken by the environment (Jayas, 2016). Heat is transported from the heating source (e.g. air) to the food surface by convection and it is transported in food by conduction. Moisture is first transported to the product surface and evaporated. It passes into the environment by convection and conduction. Heat

transfer depends on air temperature, relative humidity, air flow, environment and pressure (Ndukwu et al., 2017).

Moisture content of food depends on the surface area of food, drying time, temperature and velocity of hot air used during drying process. Drying at high temperatures is completed in a shorter time (Rurush et al., 2022). However, drying at high temperatures may cause physical and chemical changes in foods. These changes are color change, shrinkage and decomposition of carbohydrates and protein. As a result of increasing the velocity of air used for drying, drying is completed more quickly (Putra & Ajiwiguna, 2017). However, it has been determined that excessive increase in air velocity causes crust formation on the surface of the food during drying. As a result of crust formation, the center of the food remains moist (Rao et al., 2019).

Drying process can be examined in two period during the drying process (Doran, 2013). These periods are called the constant rate drying phase and the falling rate drying periods. The constant rate drying phase ends when the vapor pressure of the water in the food falls below the pressure of the saturated vapor at the same temperature (Srikiatden & Roberts, 2007). Mass transfer rate is the most important factor controlling drying progressively during falling rate period. The mass transfer rate now depends on the air temperature and the particle thickness of the dried food. In this process, the air velocity and the relative moisture of the air are not effective on the drying rate. The important factor is air temperature (Chanpet et al., 2020).

Moisture determination is one of the mostly used basic analyses in food processing and food control. The amount of moisture is an important factor affecting the durability of food. The amount of dry matter in a food is inversely proportional to the amount of water in that food (Jain & Gupta, 2005). The amount of moisture in the food is determined using direct and indirect methods. Direct and indirect methods vary according to the amount of water, sugar content and heat resistance of the food. Oven drying, distillation method, Karl Fischer titration and extraction method are some of the direct methods. Direct methods often give accurate and absolute values,

but they are manual and time-consuming. Microwave absorption, nuclear magnetic resonance and irradiation absorption are some of the indirect methods. Indirect methods are rapid, nondestructive and easily automated (Jain & Gupta, 2005).

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) are used for acquiring images inside the human body. Although the initial setup cost of NMR and MRI methods is high, the operating costs are very low (Ozel & Oztop, 2021). In this way, it becomes an effective method for repeated analyses.

NMR spectroscopy is based on the principle that places a nucleus of an atom in a very strong magnetic field and exposes it to a pulse of electromagnetic radiation. It will resonate at a specific frequency of radiation (Singh & Singh, 2022). This allows to record a spectrum and to gain structural information about the food sample. NMR spectroscopy uses radiofrequency or RF radiation. The wavelength of radiofrequency is too long and the frequency is too low (Tognarelli et al., 2015).

Low-field NMR is a subtype of NMR. This type is mainly focused on time-domain NMR measurements. Time-domain NMR studies use differences in molecular mobility between various food components. Food components are reflected in the longitudinal (T_1) and transverse (T_2) relaxation times of protons, usually that of water. The separation of a large number of water protons based on the deconvolution of the T_1 and T_2 measurements allows to gather information about different regions of mobility in foods (Tang et al., 2019). By using TD-NMR measurements, the change in the water content of the food during the drying process can be detected locally.

Therefore, the working principle of MRI is the same as NMR. In MR imaging, atomic particles interact with an external magnetic field. It emits energy at certain frequencies into the magnetic field. The emitted signal intensity represents the tissue structure (Ebrahimnejad et al., 2018).

The aim of this study is to determine the variation of moisture content of apple, chickpea and eggplant during drying in a rotary tray dryer. The change in moisture

content during drying was determined by TD-NMR and MRI methods. It was determined that these two methods were effective in measuring locational and time-dependent moisture during drying.

CHAPTER 2

LITERATURE REVIEW

2.1 Drying of Foods

Generally, foods contain high moisture contents and the purpose of drying is to reduce this moisture content. There are devices specially designed for drying and these devices are called dryers. There are many types of dryers, but the basic principle is to reduce moisture content of the foods. Tray dryers are designed for this purpose. The food is placed on the tray and drying is completed by using the tray dryer.

There are some factors that affect drying of foods. These factors are dimensions of the product, drying temperature, velocity and humidity of the air used in the drying process.

The drying rate is directly proportional to the surface area of foods and inversely proportional to the thickness. Therefore, the smaller the dried particles, the greater the surface area and the lesser the thickness. Thus, drying rate is positively affected. It has been observed that the increase in dimensions of the dried food increases the drying time of the food (Ouoba et al., 2018). When the length of one corner of the cube-shaped mashed potatoes is 6 cm, the drying time is 900 min, and when the length of one corner is 1 cm, the drying time is 300 min. The temperature of the drying environment is important. As drying temperature increases, the heat transfer rate also increases. As the heat transfer rate increases, drying is completed in a shorter time. Brasiello et al. (2013) stated that the eggplant drying at 70 °C was completed in 2 h and the drying process at 40 °C was completed in 4 h. Pinheiro et al. (2022) found that while the apple drying at 50°C was completed in 390 min, the apple drying at 35°C was completed in 600 min. The high velocity of the air used

for drying positively affects the drying time and drying rate. The humidity of the air affects the drying time. The drying process continues until there is a balance between the food and the air used for drying (Ai et al., 2022).

2.2 Moisture Content Determination

Moisture content in food directly affects the quality and shelf life of the food. Therefore, the determination of moisture content in food is very important. Direct and indirect methods have been developed to determine the moisture content. Some direct and indirect moisture content determination methods are given in Table 2.1. The chemical structure of the food is important when selecting the method for determining the moisture content.

Table 2.1. Methods used for moisture content determination in food.

Direct methods	**Indirect methods**
Oven drying	Infrared absorption
Freeze drying	NMR
Chemical desiccation	Sonic and ultrasonic absorption
Distillation methods	NIR reflectance
Karl Fischer method	Microwave absorption

The advantages and disadvantages of direct moisture content measurements are given in Table 2.2. Direct methods take a long time. The Karl Fischer method is completed in a short time, but it is difficult to determine the end point of the titration process. Oven drying method is not suitable for all food products due to temperature. For the measurement of moisture content, techniques that are completed in a shorter time and are not dependent on the chemical structure of the food should be used.

The advantages and disadvantages of indirect moisture content measurements are given Table 2.3. In these measurements, the moisture content of the food is determined using sound and magnetic field. As the moisture content in the food

decreases, its response to the applied forces changes and the amount of moisture content is determined with the help of this change. It was stated that non-direct moisture content measurements were generally non-destructive and gave rapid results. However, for non-direct methods, calibration is required since it uses another property of the food instead of measuring the moisture content directly.

Table 2.2. Advantages and disadvantages of direct methods for moisture determination.

Method	Advantages	Disadvantages
Oven drying	Typical conventional method	It is difficult to remove all of the water.
	Convenient	It is difficult to remove all of the water.
	Precision and relative speed	Loss of volatile compounds during drying
	Allows for a large number of samples	Sample decomposition (i.e., sugar)
Freeze-drying	Excellent for sensitive liquid foods	Expensive
	Maintains texture and appearance	Drying takes long time
	Not facing with foaming, case-hardening, oxidation and microbial change	Most applicable to foods with a high moisture content.
Chemical desiccation	Can be used as a reference point for other methods.	It takes a long time to reach a constant dry weight.
	Can be performed at room temperature	The strength of the desiccant affects moisture equilibrium.
	Excellent for measuring moisture in volatile compounds-containing substances.	
Karl Fischer method	A standard method for determining moisture content	To prepare the reagent, only high-purity chemicals should be used.
	The precision and accuracy are higher	Titration is performed and the end point of the titration detected visually

Source: Park, Y.W. in *Handbook of Food Analysis*, Marcel Dekker, New York, 1996, 59–92

Table 2.3. Advantages and disadvantages of indirect methods for moisture determination.

Method	Advantages	Disadvantages
IR Absorption	Multicomponent analysis is possible.	Calibration required
	More adaptable robust and selective analyzing	Temperature-dependent
	Suitable for nondestructive analysis	The sample must be homogeneous
NMR Spectroscopy	Fast and precise nondestructive method	Equipment cost is high
	Suitable method for many types of foods	Calibration curve required for different samples
	The granular structure and particle size of the food are not important	
Sonic and ultrasonic absorption	Suitable for aqueous foods and water-soluble foods	Depends on the type of media for sound transitions.
	Nondestructive	Standard substance required for moisture content determination
NIR reflectance spectroscopy	Rapid, precise and nondestructive method	Equipment cost is high
	No need for operations such as extraction	Calibration curve required
	Very small samples are sufficient	Moisture content data is affected by size, homogeneity, particle size, shape of food.
Microwave absorption	Nondestructive and relatively rapid	Results affected by size, homogeneity, particle size, shape of food
	No need for operations such as extraction	
	It gives accurate results at low frequencies.	Relatively low sensitivity and limited range

Source: Park, Y.W. in *Handbook of Food Analysis*, Marcel Dekker, New York, 1996, 59–92

2.2.1 Nuclear Magnetic Resonance and Magnetic Resonance Imaging

NMR spectrophotometers basically consist of four main parts. These are magnet, a very stable radio frequency transmitter, radio frequency receiver, recorder (monitor) containing a highly homogeneous magnetic field between the poles (Webb, 2016). An organic molecule contains many ^{1}H atoms and therefore protons, and these protons have a magnetic field that they form as a result of their rotation. With the absorption of radio waves of appropriate frequency on the molecules, protons oriented in the same direction as the magnetic field change their magnetic field to be opposite to the external field (Davidovits, 2019). The energy splitting caused by the effect of the external magnetic field gives the molecule the ability to absorb electromagnetic radiation in the radio frequency region. This forms the basis of NMR spectroscopy (Singh & Singh, 2022).

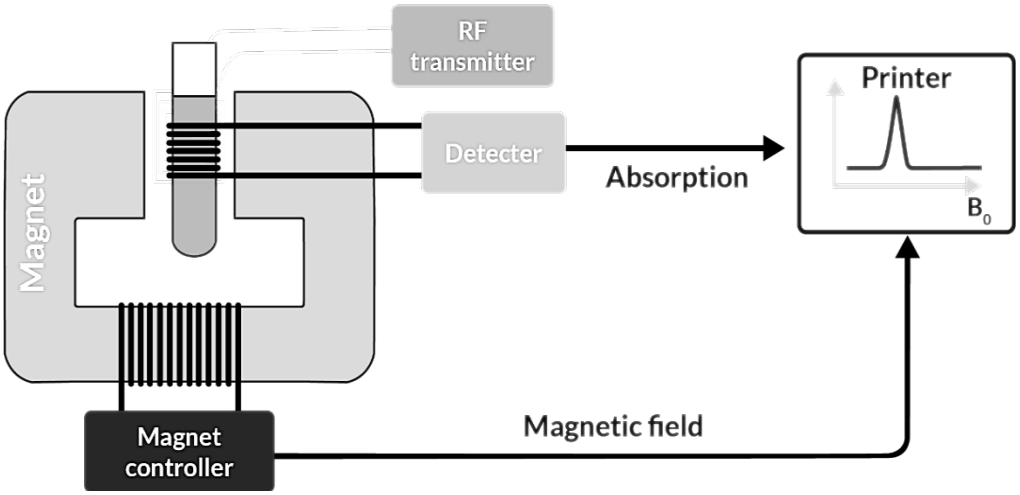

Figure 2.1. NMR spectroscopy instrumentation.

NMR Relaxometry is a technique based on the measurement of T_1 and T_2 times. T_1 and T_2 times are time constants that characterize the decrease (T_2) and increase (T_1) of the signal in different planes resulting from the short-term application of the RF signal required for NMR (Nissi et al., 2014). T_1 is known as the longitudinal oscillation and T_2 is known as the transverse oscillation time. T_1 time is characterized by an exponentially increasing signal while T_2 time is derived from an exponentially

decreasing signal curve (Deoni, 2010). The NMR Relaxation spectra, which is the output of the NMR Relaxometry experiment, is obtained by applying the Inverse Laplace method to these signal curves. NMR relaxation spectra give information about proton pools in samples (Zheng et al., 2017).

In NMR spectroscopy, the same atom resonates with different frequency values in different molecules. For example, the resonance signal formed by a free ^{1}H atom is different from the value of a ^{1}H atom in a water molecule. In the food industry, NMR spectroscopy is used for many purposes such as quality control, adulteration, and authenticity determination (Teipel et al., 2020). The components of the food can also be determined by utilizing the relaxation times obtained by the TD-NMR method. For example, it is possible to determine the amount of water in a product with TD-NMR. The amount of water in the product is an important factor in the field of food, as it affects the shelf life and usage properties of the product. (Todt et al., 2006). CPMG (Carr-Purcell-Meiboom-Gill) and IR (Inversion Recovery) techniques are often preferred for the measurement of relaxation time.

Magnetic resonance imaging has the same features as NMR. Magnetic Resonance Imaging (MRI) is a method mostly used in medicine for imaging the internal structure of living things (Chan et al., 2019). It has been widely used in the characterization of biological materials with high moisture content. It is possible to determine the quality parameters non-destructively by examining the internal structure of foods with MRI (Schork et al., 2020). Also, locational changes in the food can be detected by MRI method.

2.3 Drying Rate

During the drying process, moisture of the food is measured at certain time intervals. The moisture of foods can be determined by various direct or indirect methods, depending on the type of food. Drying rate is defined as the change in moisture content per unit time during drying.

Drying rates of solids generally consist of two or sometimes three parts that can be clearly separated from each other. These phases can be named as heating phase of the material, constant rate drying phase and the falling rate drying phase (Richardson et al., 2002).

During the constant rate drying, water layer starts to evaporate from the product. This evaporation, which does not depend on the properties of the product, is completely determined by external conditions. This type of evaporation is called the evaporation of free water in the food. While free water layer on the surface evaporates at a constant drying rate, it is constantly fed by capillary pipes formed by the air spaces between the cells (Assouline et al., 2010). In other words, during the constant rate drying, the rate of transmission of water to the surface and the rate of evaporation from the surface are equal. During the constant rate drying phase, the moisture content in the inner layers gradually decreases due to the continued moisture transport from the inner parts of the drying material to the surface. Constant rate drying continues until all free water in the food has evaporated (Keita et al., 2016). Since the physical properties of the food do not affect the drying rate in constant rate drying and the drying is completely determined by the environmental conditions, it is quite easy to calculate the drying rate at this stage. Factors such as air flow rate, total surface area of the material to be dried, temperature and moisture difference between the wet surface of the material and the air are effective on the drying rate in the constant drying rate phase (Alvarez et al., 2021).

The water carried to the surface by capillarity decreases over time and it becomes difficult to keep the surface wet because it cannot meet the amount that evaporates from the surface. From this moment on, the drying phase started at a falling drying rate. In this phase, it takes place in two stages (Shokri et al., 2009). When the water film on the surface starts to disappear, drying rate decreases in proportion to the amount of wet area. Since the transmission rate of water from the inner parts of the material to the surface is less than the evaporation rate from the surface, the thin water layer that completely covers the surface of the material disappears. From this moment on, the drying rate decrease even more (Cocusse et al., 2022). In the constant

rate drying, since the evaporation is inside the material, the water vapor that occurs reaches the surface by capillary effect. On the outer surface of the over-drying material, crusting, shrinkage and even cracks can be seen (Mercier et al., 2014). Calculation of the drying rate in the falling rate drying phase is more complex than in the constant rate drying phase. Because in this phase, there is no heat and mass transfer only by convection from the surface of the material. At this stage, heat and mass diffusion in the product must also be considered.

2.4 Aim of the Study

In this study, variation of moisture content with temperature, time and position was investigated. The drying experiment was carried out using a rotary tray dryer at 50-70 °C. The moisture contents of food samples were measured every 20 min. During drying using TD-NMR and MRI methods. The aim of this study is to determine the moisture content and drying rate of the food, apart from the classical methods. TD-NMR and MRI methods gave results very close to the actual moisture content values. In addition, it was observed that the moisture content measurements conducted by using TD-NMR and MRI methods took a short time.

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

3.1.1 Raw material

Eggplant *(Solanum melongena),* starking type apple *(Malus domestica),* canned boiled chickpeas *(Cicer arietinum)* were purchased from local markets. A blender was used to smash the boiled chickpeas. To obtain, chickpea flour was obtained. All samples were formed into cylinders for drying. The radius of this cylinder was 3 cm and its height was 1 cm.

3.2 Methods

3.2.1 Drying and Moisture Measurement

A lab scale tray dryer (Eksis Endustriyel Kurutma Sistemleri, Isparta, Turkey) was used for the drying process. The size of the trays used in drying is 30x30x2 cm. In this dryer, temperature of the air, air velocity, humidity of the air, and the rotational speed of the tray were controlled. Drying was performed at 50 °C, 60 °C and 70 °C. Other conditions kept constants were 1 m/s velocity of air, 5% relative humidity of drying air and 6 rpm tray speed.Drying took place for a total of 3 h and samples were taken every 20 min.

The oven method was used to determine the moisture content of samples by keeping in oven at 80 °C 24h. Before and after this process, the mass of the samples were measured. The moisture content of the food samples was determined from the differences.

3.2.2 Time-domain Nuclear Magnetic Resonance (TD-NMR) and Magnetic Resonance Imaging (MRI) Measurement

TD-NMR experiments were performed at 0.48 Tesla (1 H frequency of 20.34 MHz). One-centimeter dry food sample was placed in the test tube. CPMG(Carr-Purcell-Meiboom-Gill) T_2 parameter was used for data measurement. The amount of scan for measurement were set to 4. XPfit program was used to evaluate the TD-NMR signals. MRI experiments were performed at 0.05 Tesla (1 H frequency of 23.5 MHz). One-centimeter dry food sample was placed in the test tube. Spin Echo 2D imaging method was used to obtain the image of dried food samples. The obtained images were manipulated with MATLAB program for comparison. Instead of examining the whole images, a special area was selected in the images. The results from this area were compared with each other. Repetition Time (TR) is the time between series of pulses applied to the same slice. Echo Time (TE) is the time between transmitting the RF pulse and receiving the echo signal. Thickness of sample was at set at 5 mm. TR value was set at 800 ms and TE value set into 10 ms. Signal intensity was calculated using T_2 and T_1 values. Signal intensity and moisture content values were calibrated.

$$SI = M_0 * \left(1 - e^{\frac{-TR}{T_1}}\right) * (e^{\frac{-TE}{T_2}}) \quad (3.1)$$

Where, SI=Signal Intensity, M_0=Proton Intensity, T_1= Longitudinal relaxation time, T_2= Transverse relaxation time, Tr= Repetition time, TE=Echo time

3.2.2.1 Drying Rate

The amount of evaporated water or liquid per unit area and unit time is known as the drying rate. Drying rate can be expressed in general with the following formula. The unit of dry rate is kg H_2O/m^2xh.

$$R_d = \frac{-W * dM}{A * dt} \tag{3.2}$$

Where, R_d=Drying rate, W =Dry solid weight, M=Moisture value on a dry basis, t =Time, A =Area.

3.2.2.2 Statistical Analysis

Mean absolute error (MAE) and root mean square error (RMSE) were used to test the obtained predictions. These values should be low. Lower values of errors indicate that the experimental and computational model is converge well to predict the moisture profile.

$$MAE = \sum_{i=1}^{N} \left| \frac{y_{(i)} - \acute{y}_{(i)}}{N} \right| \tag{3.3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} \left| y_{(i)} - \acute{y}_{(i)} \right|^2}{N}} \tag{3.4}$$

Where, $y_{(i)}$ =actual value, $\acute{y}_{(i)}$ =predicted value, N=number of measurements

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Moisture Content Change and Drying Rate Curve

Drying experiments were carried out at 50 °C, 60 °C and 70 °C using chickpeas, apples and eggplants. Changes in moisture content according to temperature and position were determined experimentally. Cylindrical food samples were used. Therefore, the Figure 4.1 represents the foods and the sampling locations.

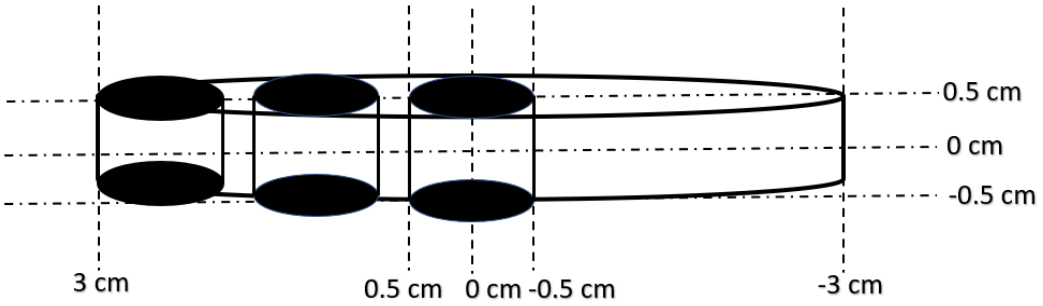

Figure 4.1. The measurement points in the dried food.

The drying experiments was repeated five times to ensure the accuracy of the data. According to these five drying experiments, the average moisture content values, standard error and coefficient of variation values of the dried food samples were calculated as percentages. Moisture content change was calculated using the amount of dry matter. Samples taken every 20 min during the experiment were kept in an oven at 80 °C for 24 h. The measured loss was used to calculate the moisture content.

When examining the drying of any material in terms of kinetics, the relationships between material moisture content and drying time, drying rate and material moisture content, drying rate and drying time, and material temperature and moisture are important parameters. There are two characteristic phases in the drying process.

These phases are constant rate drying phase and the falling rate drying phase (Inyang et al., 2018).

The drying rate per unit time and per unit area is calculated by using the moisture difference and the amount of dry matter in a certain time interval.The change in the moisture content of the dried product per unit time is called the drying rate. The time intervals of constant rate drying and falling rate drying are determined by the drying rate graphs. For this purpose, the drying vs and moisture content graph is plotted. In this graph, the x-axis shows the free moisture content and the y-axis shows the drying rate. Constant rate drying starts in the region where the graph is parallel to the x-axis.

4.1.1 Chickpea Drying

The results of drying of chickpeas are shown in the Table 4.1. Average standard error and coefficient of variance values are given in the table. The standard error and coefficient of variance of moisture content are in the acceptable range.

The moisture content of chickpeas varies between 65.15±1.82 and 23.91±1.43% for drying at 50 °C. At r=0 cm, the moisture content decreased from 65.15±1.82 to 28.94±1.34% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 26.32±0.89%. At r=3 cm, the moisture content decreased to 23.91±1.43%.

The moisture content for drying at 60 °C varies between 65.15±1.82 and 21.55±1.1%. At r=0 cm, the moisture content decreased to 26.22±1.23% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 23.78±1.7%. At r=3 cm, the moisture content decreased to 21.55±1.1%.

The moisture content for drying at 70 °C varies between 65.15±1.82 and 19.21±1.06%. At r=0 cm, the moisture content decreased to 23.36±1.86% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 21.19±1.9%. At r=3 cm, the moisture content decreased to 19.21±1.06%.

The lowest moisture was observed for 70°C for all locations. The highest moisture was observed for 50°C. The final moisture content decreased with increasing drying temperature. In addition, it was determined that the moisture content of the center of the dried chickpea was higher than the corner of the dried chickpea at the same drying temperature. At the end of drying experiment, the moisture content difference between the center and the corner is 5.03% at 50 °C, 4.67% at 60 °C and 4.15% at 70 °C. In the chickpea drying experiment, the effect of the position and temperature on the change in the moisture content of the chickpea was found to be significant ($p<0.05$).

Table 4.1. Moisture content change of chickpea.

50 °C									
	r=0 cm			r=1.5 cm			r=3 cm		
Time (min)	M%	SE	COV	M%	SE	COV	M%	SE	COV
0	65.15	1.82	0.028	65.15	1.82	0.028	65.15	1.82	0.028
20	61.55	0.81	0.014	61.15	1.72	0.03	60.75	1.66	0.03
40	56.01	1.78	0.034	55.04	0.47	0.009	54.07	0.82	0.017
60	50.97	0.86	0.018	49.53	0.84	0.018	48.12	1.83	0.041
80	46.38	1.49	0.035	44.58	0.4	0.01	42.83	0.91	0.023
100	42.21	1.8	0.048	40.12	0.42	0.012	38.12	0.79	0.023
120	38.41	1.85	0.056	36.11	1.55	0.048	33.92	1.76	0.057
140	34.95	1.23	0.042	32.5	1.72	0.061	30.19	0.78	0.029
160	31.81	1.23	0.048	29.25	1.66	0.066	26.87	1.62	0.068
180	28.94	1.34	0.059	26.32	0.89	0.042	23.91	1.43	0.071
60 °C									
	r=0 cm			r=1.5 cm			r=3 cm		
Time (min)	M%	SE	COV	M%	SE	COV	M%	SE	COV
0	65.15	1.82	0.028	65.15	1.82	0.028	65.15	1.82	0.028
20	60.92	1.78	0.031	60.42	0.84	0.015	58.93	0.85	0.016
40	54.83	1.36	0.027	53.77	0.76	0.015	51.86	1.34	0.028
60	49.35	0.75	0.016	47.86	0.87	0.02	45.64	1.08	0.025
80	44.41	1.13	0.028	42.59	1.82	0.046	40.16	1.87	0.049
100	39.97	1.2	0.034	37.91	1.09	0.032	35.34	1.96	0.061
120	35.97	1.84	0.059	33.74	1.94	0.064	31.1	0.65	0.023
140	32.38	0.85	0.031	30.03	1.24	0.048	27.37	1.02	0.042
160	29.14	0.96	0.04	26.72	1.41	0.061	24.08	0.99	0.046
180	26.22	1.23	0.059	23.78	1.7	0.086	21.19	1.9	0.105
70 °C									
	r=0 cm			r=1.5 cm			r=3 cm		
Time (min)	M%	SE	COV	M%	SE	COV	M%	SE	COV
0	65.15	1.82	0.028	65.15	1.82	0.028	65.15	1.82	0.028
20	59.33	1.08	0.02	58.93	0.85	0.016	58.53	0.87	0.017
40	52.8	1.26	0.026	51.86	1.34	0.028	50.92	1.34	0.029
60	47	1.58	0.036	45.64	1.08	0.025	44.3	1.31	0.032
80	41.83	0.87	0.022	40.16	1.87	0.049	38.54	0.87	0.024
100	37.22	1.65	0.049	35.34	1.96	0.061	33.53	1.72	0.055
120	33.13	1.6	0.054	31.1	0.65	0.023	29.17	1.68	0.061
140	29.49	0.92	0.037	27.37	1.02	0.042	25.38	1.72	0.074
160	26.24	1.57	0.071	24.08	0.99	0.046	22.08	0.97	0.048
180	23.36	1.86	0.096	21.19	1.9	0.105	19.21	1.06	0.062

1M% avarage moisture content , SE standart error, COV coefficient of variation.

Rajasekar et al.(2017) also reported differences in moisture content between the center and the corner of the chickpea during the drying performed for 4 h at 40 and 50 °C. The moisture content was observed as 43.16% at 40 °C, and at 50 °C the moisture content was 37.5%. The mechanism of the low change in moisture content despite the temperature difference is explained by the dry matter content of the chickpea. In 100 g of boiled chickpeas, there are 14 g of carbohydrates, 8 g of protein and 1.4 g of fat (Siva et al., 2019). It has been determined that the water holding capacity(whc) of chickpea and other legumes flours increases as the temperature increases(Yakoub Ladjal Ettoumi & Mohamed, 2015). It was stated that protein denaturation and structure of starch damage may be the cause of this effect. Water molecules are hydrogen bonded to the hydroxyl groups of exposed amylose and amylopectin, resulting in an increase in whc.

Lopez et al. (2015) stated that as a result of the 8 h drying process, the moisture content of chickpea was 5000 mol/cm^3 in the center, and 6178 mol/cm^3 in the corner. The initial mass concentration of chickpea was calculated as 67000 mol/cm^3. This concentration corresponds to a moisture ratio of 0.67. At the end of the drying process at 60°C, the moisture content at the center decreased to 0.05 moisture ratio and the moisture content of the corner to 0.06. After 8 h of drying, the difference in moisture content between the center and the corner is 20%.

In the drying experiment of chickpeas, constant rate drying was observed at all temperatures. The effect of temperature was observed on the constant drying rate values, and the constant drying rate values increased as a result of the increase in temperature. It was observed that the drying rate decreased with the increase of drying time.

A constant drying rate period was observed for all temperatures in chickpea samples. Because moisture content of the chickpea samples at the beginning of the drying is large, the drying rate is high. Also, the drying rate increased as a result of the increase in temperature. Temperature has an effect on drying speed of chickpeas, but location

effect is remarkable. The drying time for r=3 cm at 50°C was determined as 380 min, but for r=0 cm at 60 °C, the drying time was 380 min.

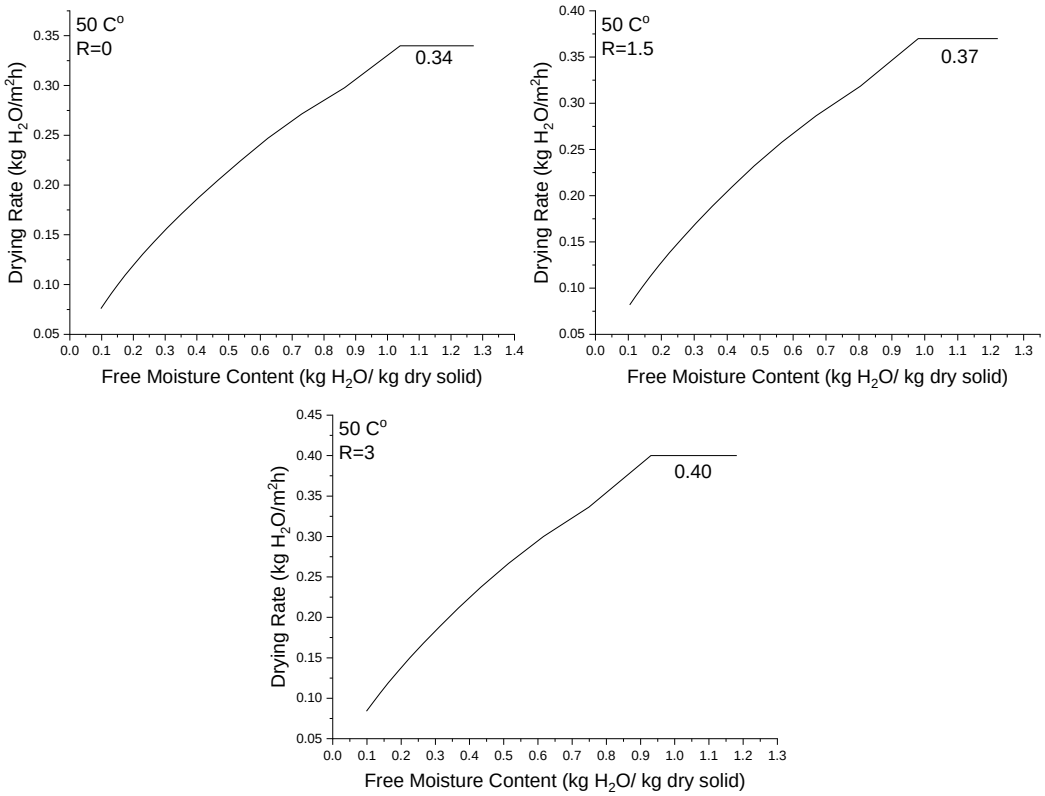

Figure 4.2. Drying rate vs free moisture content chickpea drying at 50°C.

For the chickpea drying at 50°C, the constant drying rate for r=0 cm was determined as 0.34 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 440 min. Constant drying rate for r=1.5 cm was determined as 0.37 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 400 min. Constant drying rate for r=3 cm was determined as 0.40 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 380 min.

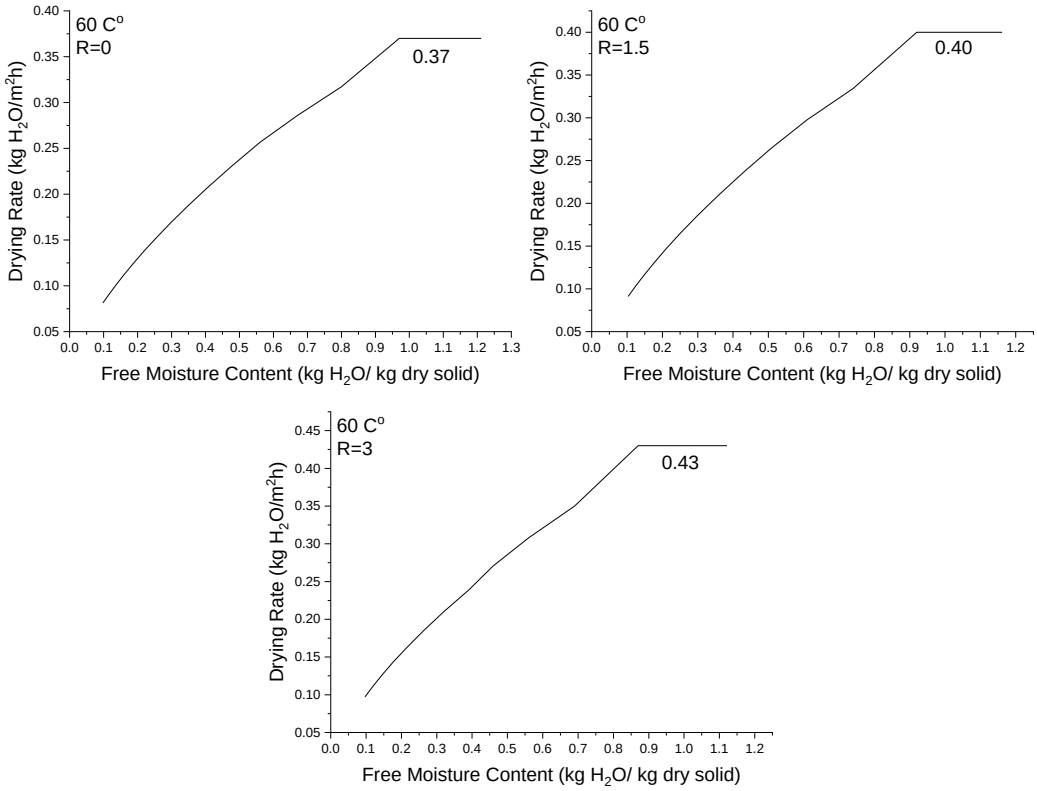

Figure 4.3. Drying rate vs free moisture content chickpea drying at 60°C.

For the chickpea drying at 60°C, the constant drying rate for r=0 cm was determined as 0.37 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 400 min. Constant drying rate for r=1.5 cm was determined as 0.40 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 360 min. Constant drying rate for r=3 cm was determined as 0.43 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 340 min.

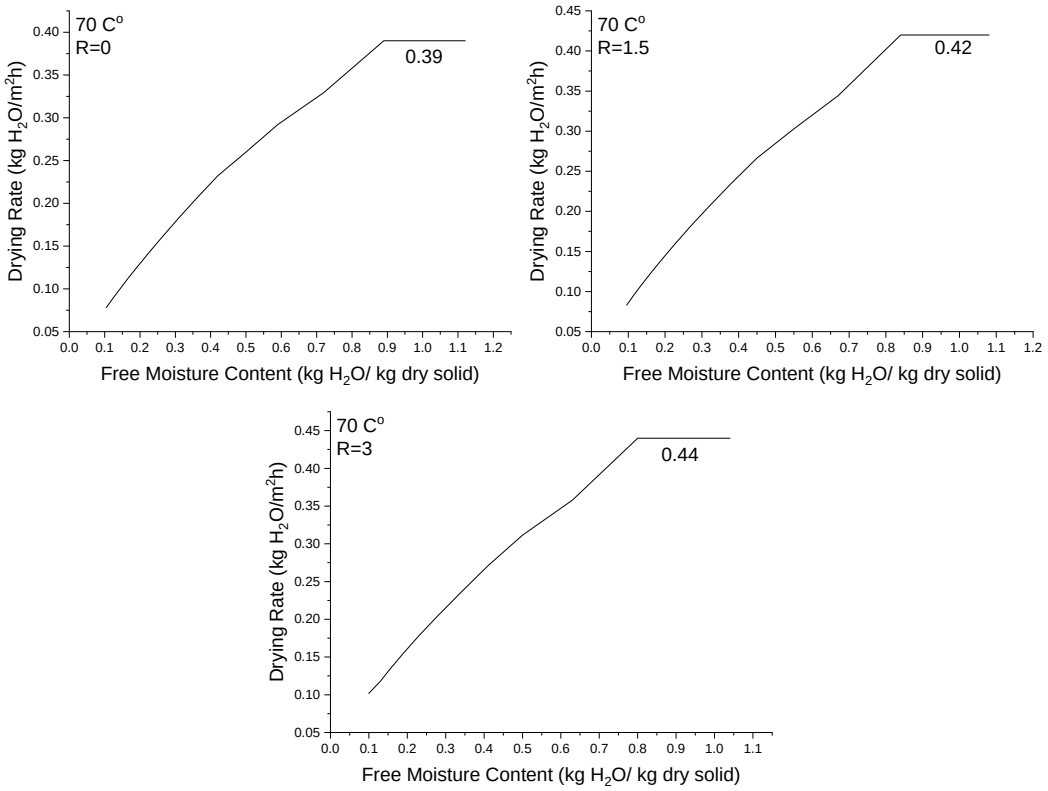

Figure 4.4. Drying rate vs free moisture content chickpea drying at 70°C.

For the chickpea drying at 70°C, the constant drying rate for r=0 cm was determined as 0.39 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 380 min. Constant drying rate for r=1.5 cm was determined as 0.42 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 340 min. Constant drying rate for r=3 cm was determined as 0.44 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 320 min.

Rajasekar et al. (2017) stated that the constant drying rate for chickpeas is 0.28 kgH_2O/m^2h at 50°C and constant drying rate for chickpeas is 0.21 kgH_2O/m^2h at 30°C. An increase in constant drying rate was observed with the increase in temperature.

4.1.2 Eggplant Drying

Eggplant drying was performed at 50°C, 60°C and 70°C. Eggplant drying experiment was carried out under the same conditions as chickpeas. The results of drying of eggplant are shown in the Table 4.2. Unlike chickpeas, eggplant has less dry matter, thus moisture content change can be easily detected when the drying temperature is changed.

During drying at 50°C, the moisture content was reduced from 87.55±1.25 to 36.77±1.35% . At r=0 cm the moisture content was reduced to 44.41±1.11% , at r=1.5 cm the moisture content was reduced to 40.08±1.98% , at r=3 cm the moisture content was reduced to 36.77±1.35% .

During drying at 60 °C, the moisture content decreased from 87.55±1.25 to 26.75±2.27%. At r=0 cm the moisture content was reduced to 36.53±0.73% , at r=1.5 cm the moisture content was reduced to 29.91±1.03% , at r=3 cm the moisture content was reduced to 26.75±2.27% .

During drying at 70 °C, the moisture content decreased from 87.55±1.25 to 19.79±1.38%. At r=0 cm the moisture content was reduced to 24.89±1.42% , at r=1.5 cm the moisture content was reduced to 22.21±1.68% , at r=3 cm the moisture content was reduced to 19.79±1.38%.

The lowest moisture was observed for 70°C and r=3 cm while highest moisture was observed for 50°C and r=0 cm. At the end of drying experiment, the moisture content difference between the center and the corner is 7.64% at 50 °C, 9.78% at 60 °C and 5.10% at 70 °C. In the eggplant drying experiment, the effect of the position and temperature on the change in the moisture content of the eggplant was found to be significant ($p<0.05$).

Table 4.2. Moisture content change of eggplant.

50 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	87.55	1.25	0.01	87.55	1.25	0.01	87.55	1.25	0.01
20	86.53	0.4	0.01	84.85	1.26	0.02	83.17	1.49	0.02
40	79.61	1.87	0.02	77.26	1.08	0.02	75.1	0.57	0.01
60	73.24	2.11	0.03	70.34	0.97	0.02	67.82	2.07	0.03
80	67.38	1.76	0.03	64.05	0.54	0.01	61.24	0.79	0.01
100	61.99	1.31	0.02	58.31	1.82	0.03	55.3	1.69	0.03
120	57.03	1.42	0.03	53.09	0.86	0.02	49.94	1.92	0.04
140	52.47	2.04	0.04	48.34	2.32	0.05	45.09	1.85	0.05
160	48.27	0.44	0.01	44.02	1.75	0.04	40.72	2.37	0.06
180	44.41	1.11	0.02	40.08	1.98	0.04	36.77	1.35	0.04
60 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	87.55	1.25	0.01	87.55	1.25	0.01	87.55	1.25	0.01
20	84.85	1.86	0.02	83.17	1.19	0.01	81.5	1.93	0.02
40	76.37	0.56	0.01	73.19	0.41	0.01	69.28	1.62	0.02
60	68.73	1.01	0.02	64.41	0.62	0.01	58.88	1.63	0.03
80	61.86	1.99	0.04	56.68	1.65	0.03	50.05	1.01	0.02
100	55.67	1.63	0.03	49.88	1.02	0.02	42.54	2.11	0.05
120	50.1	1.63	0.04	43.89	1.35	0.03	36.16	1.59	0.05
140	45.09	1.03	0.03	38.62	1.76	0.05	30.74	0.68	0.03
160	40.58	1.89	0.06	33.99	0.91	0.03	28.13	0.44	0.02
180	36.53	0.73	0.02	29.91	1.03	0.04	26.75	2.27	0.09
70 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	87.55	1.25	0.01	87.55	1.25	0.01	87.55	1.25	0.01
20	83.17	2.43	0.03	81.5	1.93	0.02	79.82	1.32	0.02
40	71.53	1.08	0.02	69.28	1.62	0.02	67.05	1.08	0.02
60	61.51	0.95	0.02	58.88	1.63	0.03	56.32	0.54	0.01
80	52.9	1.86	0.04	50.05	1.01	0.02	47.31	0.85	0.02
100	45.49	1.03	0.02	42.54	2.11	0.05	39.74	0.48	0.01
120	39.13	0.47	0.01	36.16	1.59	0.05	33.38	0.68	0.02
140	33.65	2.19	0.07	30.74	0.68	0.03	28.04	2.47	0.11
160	28.94	1.95	0.07	26.13	0.44	0.02	23.55	1.85	0.11
180	24.89	1.42	0.06	22.21	1.68	0.09	19.79	1.38	0.1

1M% avarage moisture content , SE standart error, COV coefficient of variation.

Russo et al. (2013) performed drying of eggplant at 40°C, 50°C, 60°C and 70°C for 225 min and reported that moisture content was reduced from 90% to 11%, 19% and %26 at 70, 60, 50°C respectively. Convective drying increases with increasing temperature, because the drying rate is increased. As a result, drying at high temperatures reaches the desired moisture content in a shorter time.

Putranto & Chen(2018) also reported moisture content difference of eggplant by location using a spatial engineering approach. The drying process was performed for 2 h. At the end, the moisture content of the center at the eggplant was 54% and the moisture content at the corner was 39%. Spatial moisture content variation was also reported using the magnetic resonance imaging method.

In the drying of eggplant, constant rate drying was observed at all temperatures. The effect of temperature was observed on the constant drying rate values, and the constant drying rate values increased as a result of the increase in temperature. Also, it was observed that the drying rate decreased with the increase in drying time.

A constant drying rate period was observed for all temperatures in eggplant samples. Moisture content of the eggplant samples at the beginning is very large, and thus the drying rate is high.

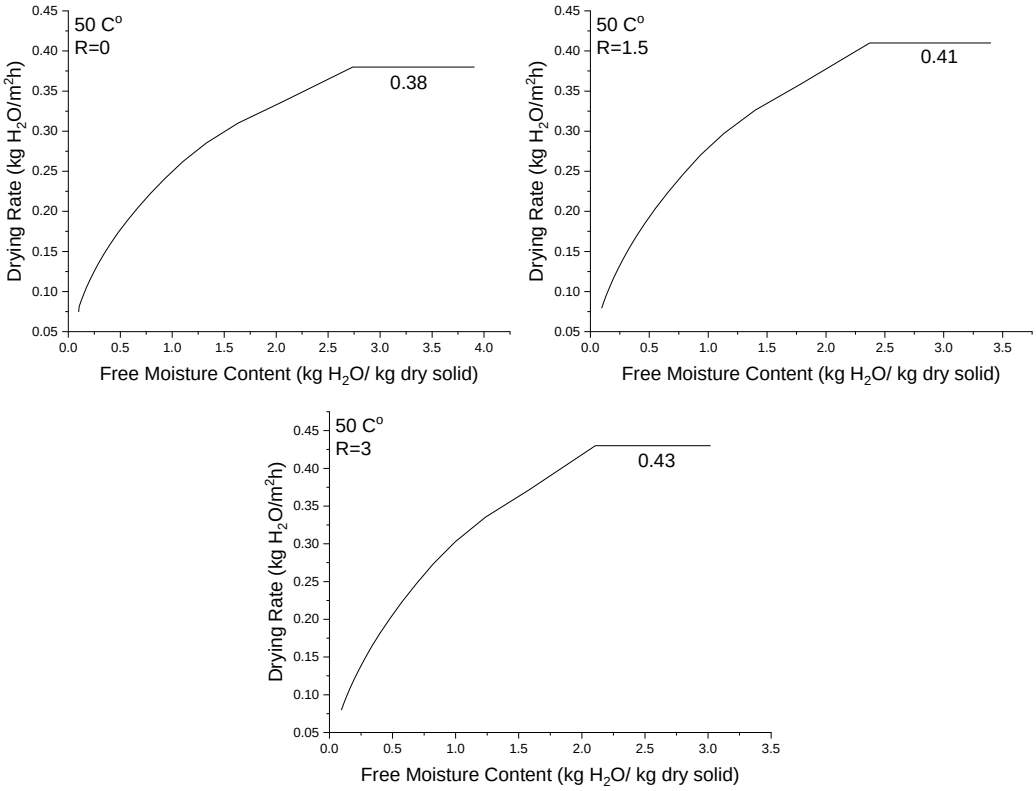

Figure 4.5. Drying rate vs free moisture content eggplant drying at 50°C.

For the eggplant drying experiment at 50°C, the constant drying rate for r=0 cm was determined as 0.38 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 460 min. Constant drying rate for r=1.5 cm was determined as 0.42 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 420 min. Constant drying rate for r=3 cm was determined as 0.44 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 400 min.

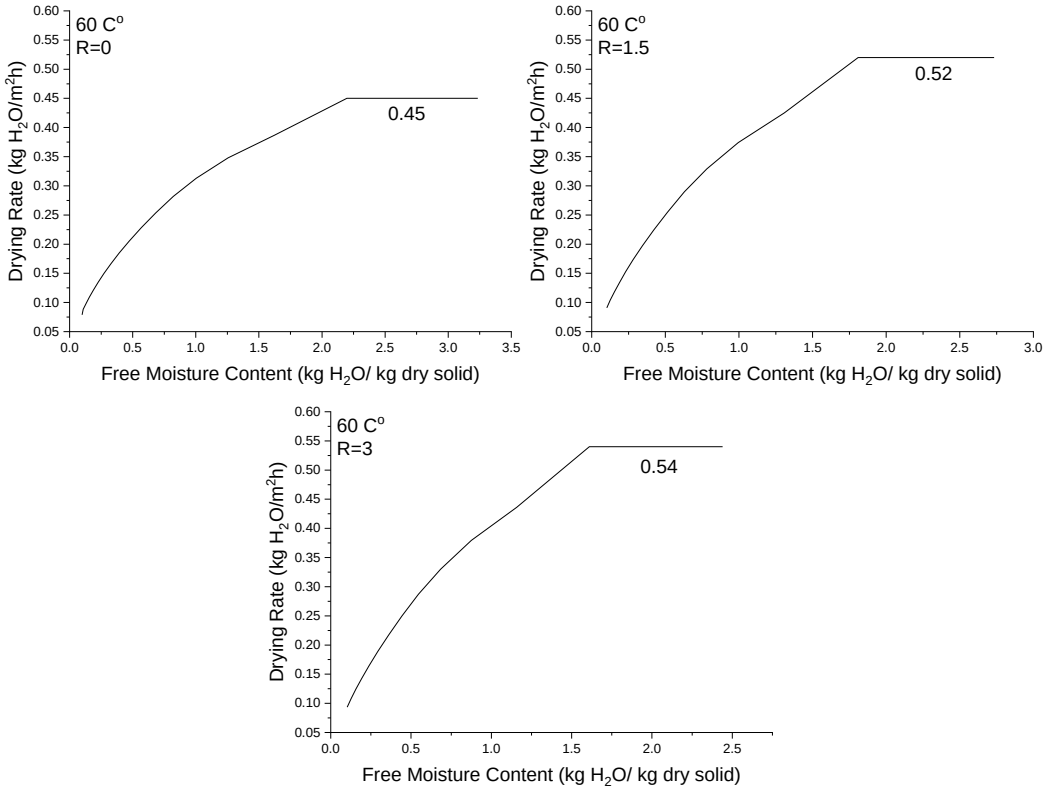

Figure 4.6. Drying rate vs free moisture content eggplant drying at 60°C.

For the eggplant drying at 60°C, the constant drying rate for r=0 cm was determined as 0.45 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 400 min. Constant drying rate for r=1.5 cm was determined as 0.52 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 360 min. Constant drying rate for r=3 cm was determined as 0.54 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 340 min.

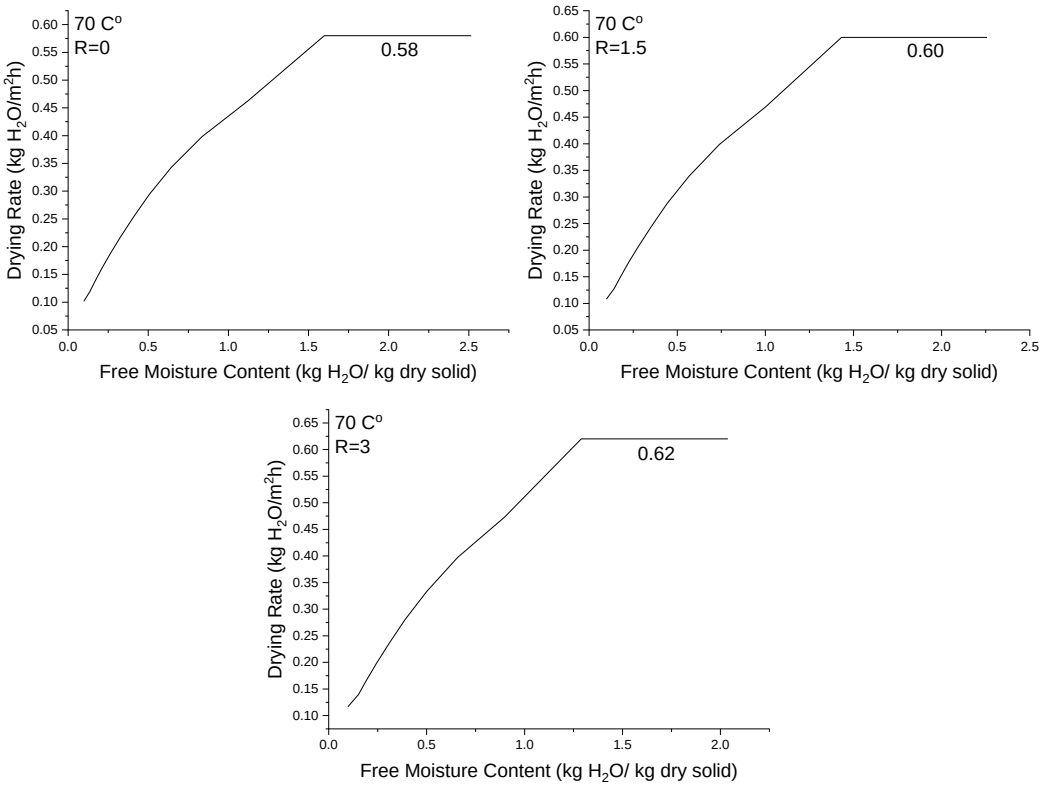

Figure 4.7. Drying rate vs free moisture content eggplant drying at 70°C.

For the eggplant drying at 70°C, the constant drying rate for r=0 cm was determined as 0.58 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 340 min. Constant drying rate for r=1.5 cm was determined as 0.60 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 320 min. Constant drying rate for r=3 cm was determined as 0.62 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 280 min.

During at 50°C, the drying time is 460 min, while in the drying experiment 70°C the drying time is 340 min. The increase in drying temperature decreases the drying time. Chayjan (2016) stated that the drying rate decreased as the moisture content decreased during the drying of eggplant. Ertekin & Yaldiz (2004) reported an increase in the drying rate as a result of increase in the drying temperature during the

drying of eggplant. The drying rate was determined as 1.89 kg water per dry matter per hour for each slice in drying performed at 60°C, and as 2.99 kg water per kg dry matter per hour for each slice in drying performed at 70°C. Sapei et al.(2017) reported that the drying rate increased as the drying temperature increased. In drying at 40°C, the constant drying rate was calculated as 0.09 kgH_2O/m^2h. However, the constant drying rate in drying at 60°C was calculated as 0.20 kgH_2O/m^2h. As the temperature of the air used for drying increases, the wet surface formed on the surface of the food dries faster. Evaporation of water occurs at any temperature, but as the temperature of the air increases, the rate of evaporation increases as well.

4.1.3 Apple Drying

Apple drying was performed at 50°C, 60°C and 70°C. Apple drying experiment was carried out under the same conditions as chickpea and eggplant drying experiment.

The moisture content for drying at 50 °C varies between 84.55±1.47 and 17.22±0.96% . At r=0 cm, the moisture content decreased to 39.11±1.05% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 35.38±0.34% . At r=3 cm, the moisture content decreased to 31.96±0.48% .

The moisture content for drying at 60 °C varies between 84.55±1.47 and 23.64±1.64% . At r=0 cm, the moisture content decreased to 29.01±1.69% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 26.20±0.47% . At r=3 cm, the moisture content decreased to 23.64±1.64% .

The moisture content for drying at 70 °C varies between 84.55±1.47 and 17.22±0.96% . At r=0 cm, the moisture content decreased to 21.30±1.72% after 3 h of drying. At r=1.5 cm, the moisture content decreased to 19.16±1.41% . At r=3 cm, the moisture content decreased to 17.22±0.96% .

As the temperature increased, a decrease in moisture content was observed and the lowest moisture content was measured at 70°C. In addition, a change in moisture content was observed depending on the location. The lowest moisture content during

drying experiment was observed for r=3 cm. After 3 h of drying, the difference between the center and the corner at 50 °C were 7.15% , between the center and the corner at 60 °C was 5.37% , and the difference between the center and the corner at 70 °C was 4.07% . In the apple drying experiment, the effect of the position and temperature on the change in the moisture content of the apple was found to be significant ($p<0.05$).

Table 4.3. Moisture content change of apple.

50 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	84.55	1.47	0.017	84.55	1.47	0.017	84.55	1.47	0.017
20	83.17	0.91	0.011	82.18	0.7	0.009	81.19	0.37	0.005
40	75.68	0.57	0.008	73.96	1.63	0.023	72.26	1.16	0.017
60	68.87	1.53	0.024	66.57	0.39	0.006	64.31	0.6	0.01
80	62.67	0.41	0.007	59.91	1.52	0.026	57.24	0.42	0.008
100	57.03	1.72	0.031	53.92	1.67	0.031	50.94	0.74	0.015
120	51.9	1.35	0.026	48.53	0.65	0.013	45.34	0.87	0.019
140	47.23	1.1	0.023	43.67	1.35	0.028	40.35	1.5	0.036
160	42.98	1.1	0.023	39.31	1.38	0.03	35.91	1.04	0.026
180	39.11	1.05	0.023	35.38	0.34	0.007	31.96	0.48	0.012
60 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	84.55	1.47	0.017	84.55	1.47	0.017	84.55	1.47	0.017
20	80.66	1.22	0.015	79.82	0.45	0.006	78.99	1.12	0.014
40	70.98	0.85	0.013	69.44	0.34	0.005	67.93	0.99	0.016
60	62.46	1.25	0.022	60.42	0.58	0.011	58.42	1.65	0.032
80	54.97	1.04	0.021	52.56	0.96	0.02	50.24	0.71	0.015
100	48.37	1.45	0.032	45.73	1.27	0.03	43.21	1.8	0.044
120	42.57	1.14	0.029	39.78	0.92	0.025	37.16	1.09	0.032
140	37.46	0.85	0.025	34.61	1.16	0.036	31.96	0.97	0.034
160	32.96	0.34	0.011	30.11	0.86	0.03	27.48	0.58	0.022
180	29.01	1.69	0.057	26.2	0.47	0.018	23.64	1.64	0.067
70 °C									
	r=0 cm			**r=1.5 cm**			**r=3 cm**		
Time (min)	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**	**M%**	**SE**	**COV**
0	84.55	1.47	0.017	84.55	1.47	0.017	84.55	1.47	0.017
20	78.15	0.32	0.004	77.31	0.89	0.012	76.47	0.66	0.009
40	66.43	1.05	0.017	64.94	1.47	0.025	63.47	1.55	0.027
60	56.46	0.34	0.007	54.55	0.66	0.014	52.68	0.58	0.012
80	47.99	1.7	0.04	45.82	0.5	0.012	43.72	0.36	0.009
100	40.79	0.47	0.013	38.49	0.33	0.009	36.29	1.51	0.045
120	34.68	0.69	0.022	32.33	0.38	0.013	30.12	1.07	0.04
140	29.47	1.45	0.057	27.16	1.04	0.044	25	1.19	0.059
160	25.05	1.79	0.085	22.81	1.21	0.062	20.75	1.59	0.098
180	21.3	1.72	0.088	19.16	1.41	0.083	17.22	0.96	0.075

1M% avarage moisture content , SE standart error, COV coefficient of variation.

Yuan et al. (2019) reported that physical changes in apples can be determined using magnetic resonance imaging. Slap-shaped apples were used in the drying experiment and the dimensions of the apple were 5x5x2 cm and drying experiment performed at 60°C. At the end of the drying, 10% moisture content difference was determined between the center and the corner of the apple.

Fanek (2012) also reported moisture content differences between center and corner during marshmallow drying. The moisture content at the center was reported as 35% and the corner was 10% at the end of 4-day drying for cylinder shape marshmallows. It was determined that the difference in external mass transfer between the center and the corner of the dried marshmallow during drying was very large. The reason for the difference in external mass transfer is so large is that the corner of the food sample can transfer heat and mass transfer from three directions, while the center of the food sample uses only two directions.

Arunsandeep & Chandramohan(2018) reported that relationship between the drying rate and the dimensions of the dried material. In the cylindrical food drying study, it was determined that the moisture content was higher in the center of the food. While the moisture content in the center of the food was calculated as 0.290 g/g, the moisture content in the corner of the food was calculated as 0.271g/g. Moisture is removed from the surface during the first drying phase. Internal moisture diffuses from the inside to the surface due to the moisture gradient, thus reducing the mass of the object continuously.

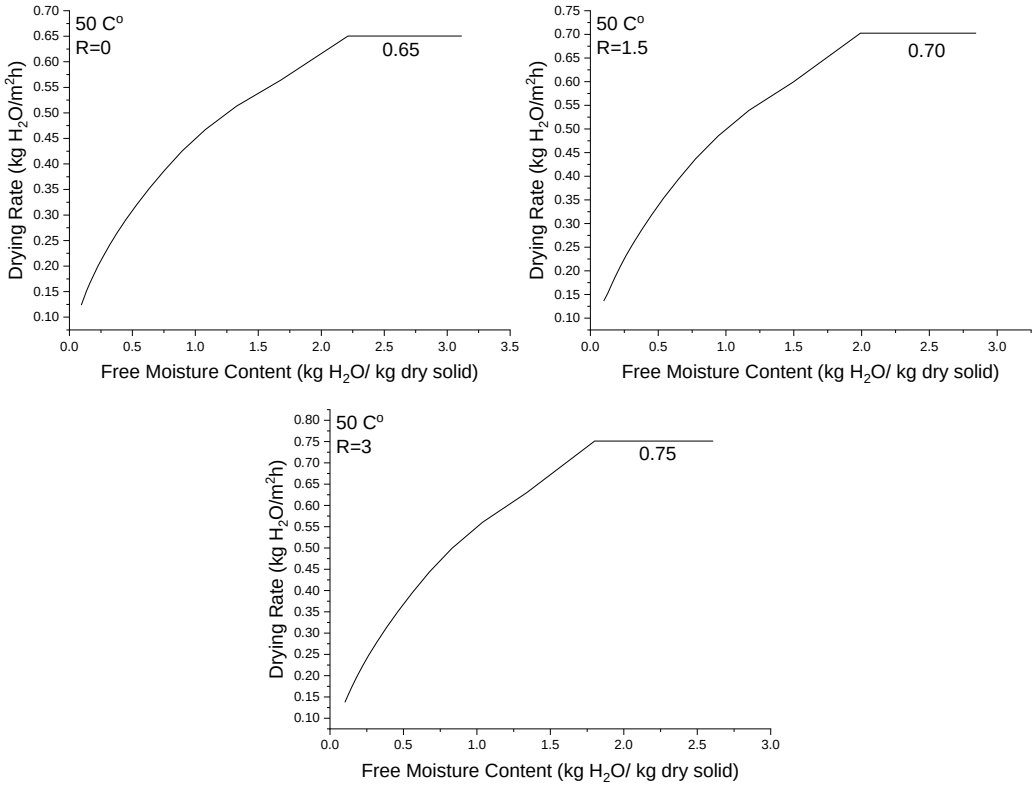

Figure 4.8. Drying rate vs free moisture content apple drying at 50°C.

For the apple drying experiment at 50°C, the constant drying rate for r=0 cm was determined as 0.65 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 420 min. Constant drying rate for r=1.5 cm was determined as 0.70 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 380 min. Constant drying rate for r=3 cm was determined as 0.75 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 360 min.

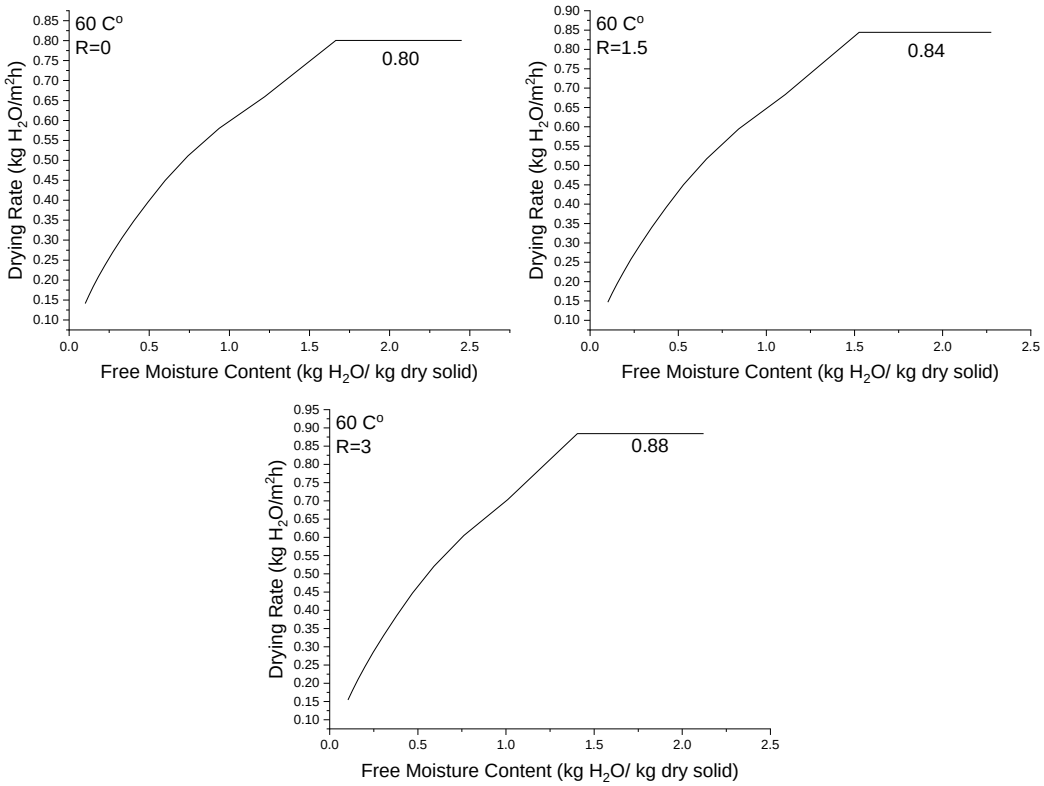

Figure 4.9. Drying rate vs free moisture content apple drying at 60°C.

For the apple drying experiment at 60°C, the constant drying rate for r=0 cm was determined as 0.80 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 340 min. Constant drying rate for r=1.5 cm was determined as 0.84 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 320 min. Constant drying rate for r=3 cm was determined as 0.88 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 300 min.

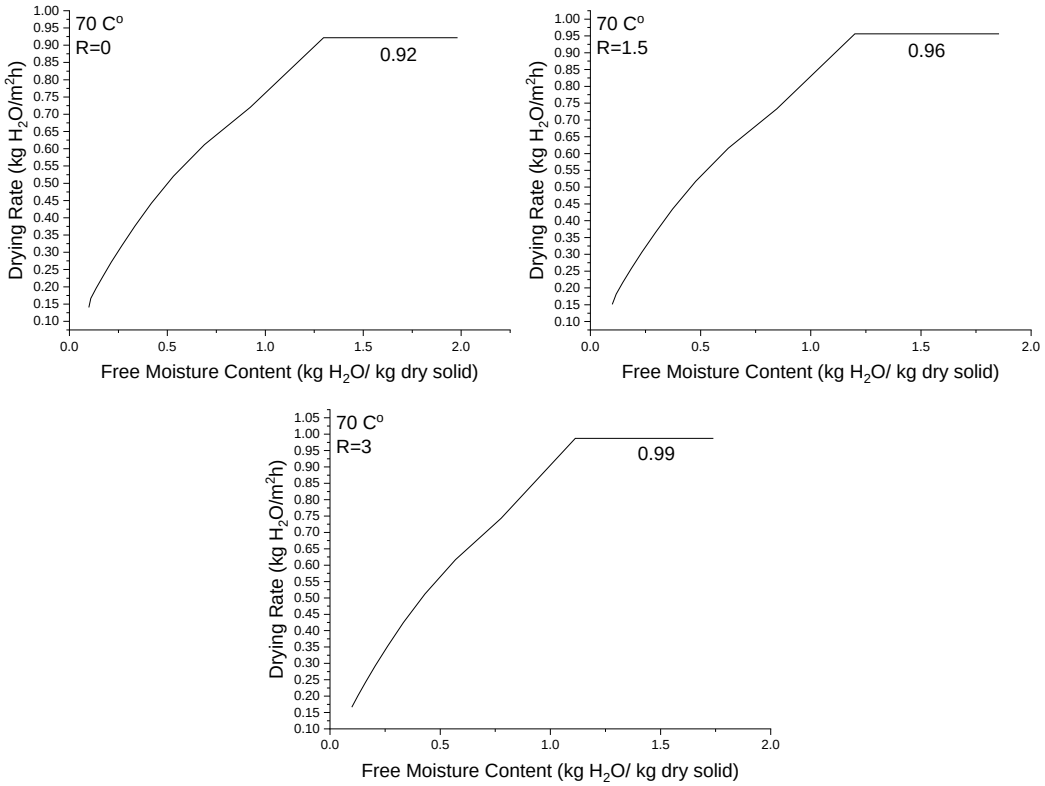

Figure 4.10. Drying rate vs free moisture content apple drying at 70°C.

For the apple drying experiment at 70°C, the constant drying rate for r=0 cm was determined as 0.92 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 300 min. Constant drying rate for r=1.5 cm was determined as 0.96 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 280 min. Constant drying rate for r=3 cm was determined as 0.99 kgH_2O/m^2h and the time required for the moisture content to decrease to 10% was determined as 260 min.

The effects of location and temperature of on drying rate and drying are evident. The increase in the drying temperature had a positive effect on the drying rate and drying time. As a result of the increase in location, the moisture content, drying rate and drying time of the food decreased. The moisture content of samples taken from the center of the food is higher than the moisture content of samples taken from the corner of the food. It was determined that the center of the food needs longer time to dry than the corner of the food.

In the drying experiment, constant rate drying was observed in the tested food samples. Constant rate drying ended with the decrease of moisture content. While drying continues at a constant rate, the moisture content of the food decreases due to drying, and the moisture in the interior of the food can no longer diffuse to the outer surface to form a continuous liquid medium layer. On the outer surface of the food, dry spots begin to form from place to place on the dried outer surface. Therefore, the drying rate begins to decrease. The number of dry spots in the food has increased and enlarged. As the moisture content of the food decreases, its heat permeability also decreases, and this causes a decrease in the drying rate of the moisture to be carried to the surface and a continuous decrease in the drying rate. The drying process continues until the vapor pressure of moisture is equalized between the food and drying air.

4.2 Time Domain Nuclear Magnetic Resonance Results

Since some of the protons of the ^{1}H atom in foods are in fixed positions bound to free-flowing water molecules and other ^{1}H protons to protein, fat and carbohydrate structural or energy-storing molecules, there are molecular structure-specific differences in the T_1 and T_2 relaxation times. T_1 and T_2 relaxation times, which depend on the environment where the protons are located, allow the detection of the molecular structures in which the relevant atoms are located (Younas et al., 2021).

T_2 values of the dried chickpea, eggplant, and apple were measured using TD-NMR every 20 min during the drying process. In the signal intensity equation(4.1), TE (echo time) was set at 10 ms and TR (repetition time) was set at 800 ms.

$$SI = M_0 * \left(1 - e^{\frac{-TR}{T_1}}\right) * (e^{\frac{-TE}{T_2}}) \quad (4.1)$$

Since the repetition time is 800 ms and the maximum T_1 value is 87ms, the second multiplier can be accepted as 1. When the equation is rewritten:

$$SI = M_0 * (e^{\frac{-TE}{T_2}}) \quad (4.2)$$

Calibration curve was prepared using experimentally measured moisture content results and signal intensity results measured using TD-NMR.

4.2.1 TD-NMR Result for Chickpea Drying

For the chickpea drying, a decrease in proton intensity and transverse relaxation time was observed as a result of the decrease in moisture content. It was determined that the decrease in the amount of unbound water in chickpea caused a decrease in the TD-NMR signal. In addition, it was determined that the increase in drying temperature affected the moisture content. For the same drying times, the moisture

content decreased rapidly as the drying temperature increased. It was detected in TD-NMR signals and transverse relaxation time. This was determined that the moisture content of the center of the chickpea was higher than the corner during drying, and this was supported by TD-NMR signals and transverse relaxation times. However, it was determined that the effect of increasing the drying temperature on chickpea was less effective than the location effect.

At 50 °C, the T_2 value ranged from 260.60±27.66 to 43.38±13.13 ms. Signal intensity ranged from 12.18±0.31 to 3.19±0.22. At r=0 cm the signal intensity decreased to 3.50±0.19, at r=1.5 cm the signal intensity decreased to 3.36±0.58, and at r=3 cm the signal intensity decreased to 3.19±0.22. At 60 °C, the T_2 value range from 260.60±27.66 to 43.38±13.13 ms. Signal intensity ranged from 12.18±0.31 to 2.65± 0.09. At r=0 cm the signal intensity decreased to 3.32± 0.31, at r=1.5 cm the signal intensity decreased to 2.88± 0.22, and at r=3 cm the signal intensity decreased to 2.48± 0.09. At 70 °C, the T_2 value range from 260.60±27.66 to 36.85± 15.4 ms. Signal intensity ranged from 12.18±0.31 to 2.33± 0.30. At r=0 cm the signal intensity decreased to 3.14± 0.24, at r=1.5 cm the signal intensity decreased to 2.72± 0.16, and at r=3 cm the signal intensity decreased to 2.33± 0.30.

Signal intensity and transverse relaxation time decreased with increasing drying temperature. The lowest signal intensity was measured for r=3 cm at 70°C and the highest signal intensity was measured for r=0 cm at 50°C. In addition, the transverse relaxation time varied according to the location of the sample taken from the dried chickpea. As the drying time increases, the moisture content decreases. Since TD-NMR measures the number of protons in food, signal intensity decreases with increasing drying time.

Table 4.4. TD-NMR results of chickpea drying.

			T_2 (ms)		**M_0(kg^{-1})**		**SI (kg^{-1})**	
Temperature °C	Position (cm)	Time (min)	Average Value	Standard Error	Average Value	Standard Error	Average Value	Standard Error
50	**r=0**	0	260.6	27.66	12.65	0.45	12.18	0.31
		60	139.55	15.05	10.33	0.49	9.62	0.25
		120	88.96	27.68	6.87	0.27	6.14	0.19
		180	48.69	16.25	4.3	0.35	3.5	0.19
	r=1.5	0	260.6	27.66	12.65	0.32	12.18	0.23
		60	134.61	21.96	9.63	0.73	8.94	0.46
		120	86.13	18.62	6.23	0.74	5.55	0.43
		180	45.69	13.8	3.81	0.88	3.36	0.58
	r=3	0	260.6	27.66	12.65	0.61	12.18	0.42
		60	129.39	15.69	8.91	0.6	8.25	0.32
		120	82.74	15.77	5.58	0.6	4.95	0.32
		180	43.38	13.13	3.34	0.33	3.19	0.22
60	**r=0**	0	260.6	27.66	12.65	0.45	12.18	0.31
		60	133.91	11.42	10.19	1.04	9.45	0.43
		120	83.6	26.79	6.7	0.87	5.94	0.6
		180	44.88	11.35	4.14	0.74	3.32	0.31
	r=1.5	0	260.6	12.13	12.65	0.53	12.18	0.23
		60	129.18	14.41	9.48	0.89	8.78	0.45
		120	80.95	26.75	6.07	0.94	5.36	0.65
		180	42.12	19.7	3.66	0.37	2.88	0.22
	r=3	0	260.6	21.28	12.65	0.25	12.18	0.15
		60	124.16	13.11	8.77	0.76	8.09	0.35
		120	77.75	19.49	5.42	0.83	4.76	0.49
		180	39.98	10.51	3.05	0.15	2.65	0.09
70	**r=0**	0	260.6	27.66	12.65	0.45	12.18	0.31
		60	128.51	13.98	10.05	0.74	9.3	0.36
		120	78.58	16.2	6.54	0.19	5.76	0.1
		180	41.37	15.75	4	0.45	3.14	0.24
	r=1.5	0	260.6	13.54	12.65	0.16	12.18	0.08
		60	123.98	20.55	9.35	0.27	8.62	0.16
		120	76.07	23.53	5.91	0.46	5.18	0.3
		180	38.82	21.39	3.51	0.26	2.72	0.16
	r=3	0	260.6	15.28	12.65	0.2	12.18	0.1
		60	119.17	24.43	8.63	0.51	7.94	0.34
		120	73.08	16.26	5.27	0.77	4.59	0.42
		180	36.85	15.4	2.48	0.57	2.33	0.3

1These are the results obtained from 5 different measurements and the averages of the measurements are used. T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error.

Moisture content and TD-NMR results were measured for all drying temperatures. TD-NMR signal intensity and moisture content were plotted in Figure 4.11. The linear fitting method was used by using the measured signal intensity values and moisture content values. In the equation, the slope was calculated as 4.66, the intercept as 10.14 and R^2 as 0.99.

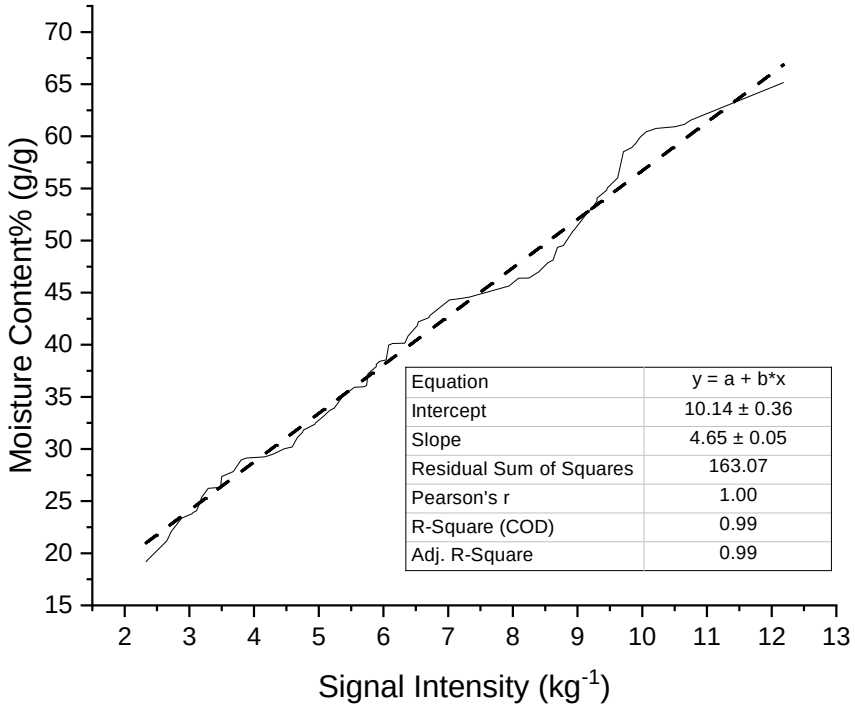

Figure 4.11. Signal intensity and moisture content calibration curve of chickpea drying.

Moisture content values obtained as a result of fitting were compared to experimental values, and RMSE and MAE values were calculated. RMSE values are low for chickpea drying experiment. The lower the RMSE values, the better for modeling and fitting. The lowest RMSE value was observed at 60°C at r=0 cm and the highest RMSE value was observed at 50°C at r=3 cm. Although some moisture values are far from fitted values, RMSE and MAE values are not high. During the drying

experiment of the chickpea, fluctuation was observed in the fitting, since the corner of the chickpea was lower in moisture content. It was concluded that the TD-NMR method can be used to determine the moisture content for chickpea drying.

Table 4.5. Statistical analysis of TD-NMR signal intensity of chickpea drying experiment.

	Temperature °C								
	50			**60**			**70**		
	r=0 (cm)	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**
MAE	1.89	2.00	2.38	1.62	1.58	2.09	2.31	2.03	2.19
RMSE	2.20	2.37	3.30	2.00	2.04	2.95	2.92	2.44	2.79
R^2	0.91	0.91	0.89	0.91	0.91	0.89	0.91	0.91	0.9

1Mean absolute error (MAE), root mean square error (RMSE) and R^2 results of chickpea drying.

4.2.2 TD-NMR Result for Eggplant Drying

In the eggplant drying experiments, a decrease in moisture content caused a decrease in proton intensity and transverse relaxation times. It was observed that as the amount of unbound water in eggplant decreased, so did the TD-NMR signal and transverse relaxation time. Furthermore, it was observed that increasing the drying temperature had an effect on the moisture content. The moisture content decreased drastically as the drying temperature increased for the same drying period. Also, it was detected in TD-NMR signals and transverse relaxation time of eggplant. During drying, the moisture content in the center of the eggplant was higher than in the corner of the eggplant, and this was supported by the TD-NMR signals and transverse relaxation times.

At 50 °C, the T_2 value ranges from 437.75±29.12 to 116.49±24.35 ms. Signal intensity ranged from 14.42±0.33 to 4.96±0.23. At r=0 cm the signal intensity

decreased to 6.62±0.21, at r=1.5 cm the signal intensity decreased to 5.87±0.32, and at r=3 cm the signal intensity decreased to 4.96±0.23.

At 60 °C, the T_2 value ranges from 437.75±29.12 to 77.02±21.59 ms. Signal intensity ranged from 14.42±0.33 to 3.72±0.10. At r=0 cm the signal intensity decreased to 5.57±0.34, at r=1.5 cm the signal intensity decreased to 4.91±0.29, and at r=3 cm the signal intensity decreased to 3.72±0.10.

At 70 °C, the T_2 value ranges from 437.75±29.12 to 45.47±16.21 ms. Signal intensity ranged from 14.42±0.33 to 2.65±0.32. At r=0 cm the signal intensity decreased to 4.27±0.26, at r=1.5 cm the signal intensity decreased to 3.43±0.17, and at r=3 cm the signal intensity decreased to 2.65±0.32.

Table 4.6. TD-NMR results of eggplant drying.

			T_2 (ms)		**M_0(kg^{-1})**		**SI (kg^{-1})**	
Temperature °C	Position (cm)	Time (min)	Average Value	Standard Error	Average Value	Standard Error	Average Value	Standard Error
50	**r=0**	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	266.91	15.84	12.35	0.52	11.89	0.28
		120	194.55	29.14	9	0.28	8.55	0.2
		180	150.69	17.11	7.07	0.37	6.62	0.21
	r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	257.07	23.12	11.62	0.77	11.18	0.5
		120	194.55	19.6	8.5	0.78	8.07	0.47
		180	135.99	25.05	6.32	0.47	5.87	0.32
	r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	243.94	16.52	10.82	0.63	10.38	0.34
		120	163.83	16.6	7.28	0.63	6.84	0.34
		180	116.49	24.35	5.41	0.35	4.96	0.23
60	**r=0**	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	250.53	12.02	12.04	1.09	11.57	0.47
		120	160.75	28.2	8.23	0.92	7.74	0.65
		180	98.06	11.95	5.57	0.78	5.03	0.34
	r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	234.1	15.17	11.17	0.94	10.7	0.49
		120	154.58	28.16	7.57	0.99	7.1	0.69
		180	87.54	20.74	4.91	0.47	4.38	0.29
	r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	230.81	13.8	10.56	0.8	10.11	0.39
		120	142.29	20.52	6.76	0.87	6.3	0.53
		180	77.02	21.59	4.24	0.16	3.72	0.1
70	**r=0**	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	237.36	14.72	11.79	0.78	11.3	0.4
		120	139.24	17.05	7.75	0.2	7.21	0.11
		180	74.39	16.58	4.89	0.47	4.27	0.26
	r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	220.97	21.63	10.91	0.28	10.43	0.18
		120	123.86	24.77	6.86	0.48	6.33	0.32
		180	58.62	22.52	4.06	0.27	3.43	0.17
	r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
		60	214.38	25.72	10.23	0.54	9.76	0.37
		120	111.57	17.12	6.03	0.81	5.51	0.45
		180	45.47	16.21	3.3	0.6	2.65	0.32

1These are the results obtained from 5 different measurements and the averages of the measurements are used. T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error.

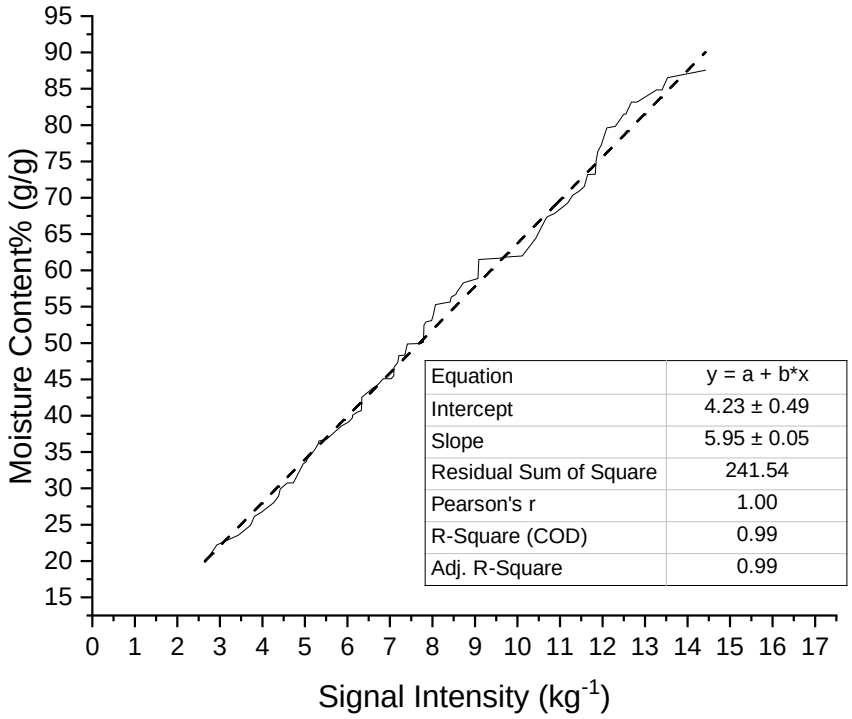

Figure 4.12. Signal intensity and moisture content calibration curve of eggplant drying.

Moisture content and TD-NMR results were measured for eggplant drying experiment. TD-NMR signal intensity and moisture content were plotted in Figure 4.12. The linear fitting method was used by using the measured signal intensity values and moisture content values. In the equation, the slope was calculated as 5.95, the intercept as 4.23, and R^2 as 0.99.

Moisture content values obtained as a result of fitting were compared with experimental values and RMSE values were calculated. The lower the RMSE values, the better modeling and fitting. The lowest RMSE value was observed at 60°C and r=1.5 cm and the highest RMSE value was observed and 50°C at r=3 cm. It has been

concluded that the TD-NMR method can be used to determine the moisture content for eggplant during drying.

Table 4.7. Statistical analysis of TD-NMR signal intensity of eggplant drying experiment.

	Temperature °C								
	50			**60**			**70**		
	r=0 (cm)	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**
MAE	2.45	2.33	5.15	2.33	1.92	2.19	2.96	3.39	3.51
RMSE	2.95	2.87	5.61	2.73	2.22	2.71	3.69	3.92	4.12
R^2	0.92	0.92	0.91	0.93	0.93	0.92	0.92	0.93	0.92

1Mean absolute error (MAE), root mean square error (RMSE) and R^2 results of eggplant drying.

4.2.3 TD-NMR Result for Apple Drying

In the apple drying, results similar to eggplant and chickpea drying were obtained. A decrease in TD-NMR signal and transverse relaxation time was observed as a result of the decrease in moisture content of apples. Transverse relaxation time for apple drying decreased with time as a result of decreasing moisture content. Similar changes were observed in proton intensity and signal intensity. Signal intensity change was observed with the location and temperature during apple drying.

At 50 °C, the T_2 value ranges from 422.75±27.24 to 202.25±15.04 ms. Signal intensity ranged from 12.98±0.68 to 5.41±0.13. At r=0 cm the signal intensity decreased to 6.32±0.29, at r=1.5 cm the signal intensity decreased to 5.89±0.27, and at r=3 cm the signal intensity decreased to 5.41±0.13.

At 60 °C, the T_2 value ranges from 422.75±27.24 to 122.65±21.59 ms. Signal intensity ranged from 12.98±0.68 to 3.72±0.32. At r=0 cm the signal intensity decreased to 4.60±0.20, at r=1.5 cm the signal intensity decreased to 4.06±0.23, and at r=3 cm the signal intensity decreased to 3.72±0.32.

At 70 °C, the T_2 value ranges from 422.75±27.24 to 64.00±19.39 ms. Signal intensity ranged from 12.98±0.68 to 2.50±0.15. At r=0 cm the signal intensity decreased to 3.54±0.15, at r=1.5 cm the signal intensity decreased to 3.07±0.24, and at r=3 cm the signal intensity decreased to 2.50±0.15.

Table 4.8. TD-NMR results of apple drying.

			T_2 (ms)		**M_0(kg^{-1})**		**SI (kg^{-1})**	
Temperature °C	Position (cm)	Time (min)	Average Value	Standard Error	Average Value	Standard Error	Average Value	Standard Error
50	**r=0**	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	319.55	23.05	10.61	0.49	10.28	0.32
		120	256.7	17.18	8.02	0.22	7.72	0.12
		180	231.55	12.7	6.6	0.64	6.32	0.29
	r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	303.55	12.6	10.08	1.15	9.75	0.52
		120	243.85	18.89	7.56	0.53	7.25	0.31
		180	219.95	13.08	6.16	0.58	5.89	0.27
	r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	302.75	23.25	9.95	0.87	9.62	0.57
		120	227.35	19.17	7.11	1.3	6.8	0.77
		180	202.25	15.04	5.69	0.25	5.41	0.13
60	**r=0**	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	286	19.32	9.94	0.63	9.6	0.38
		120	198.05	16.69	6.85	0.91	6.51	0.5
		180	147.8	15.75	4.93	0.37	4.6	0.2
	r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	273.45	17.26	9.48	0.73	9.14	0.41
		120	185.5	11.86	6.39	0.38	6.05	0.16
		180	131.05	13.15	4.38	0.5	4.06	0.23
	r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	260.9	27.43	9.11	0.64	8.77	0.44
		120	172.9	16.87	6.02	0.76	5.68	0.42
		180	122.65	13.46	4.09	0.67	3.77	0.32
70	**r=0**	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	256.7	17.67	9.35	0.43	9	0.24
		120	156.15	27.44	6.01	0.93	5.64	0.65
		180	97.5	12.88	3.92	0.33	3.54	0.15
	r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	244.15	19.28	8.89	0.32	8.54	0.19
		120	147.8	20.21	5.64	1.18	5.27	0.72
		180	84.95	12.86	3.46	0.53	3.07	0.24
	r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
		60	235.75	18.51	8.61	0.58	8.25	0.34
		120	135.2	22.29	5.26	0.89	4.89	0.57
		180	64	19.39	2.92	0.25	2.5	0.15

1These are the results obtained from 5 different measurements and the averages of the measurements are used. T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error.

Moisture content and TD-NMR results were measured for all drying temperatures. TD-NMR signal intensity and moisture content were plotted in Figure 4.13. The linear fitting method was used by using the measured signal intensity values and moisture content values. In the equation, the slope was calculated as 6.74, the intercept as -0.6, and R^2 as 1.

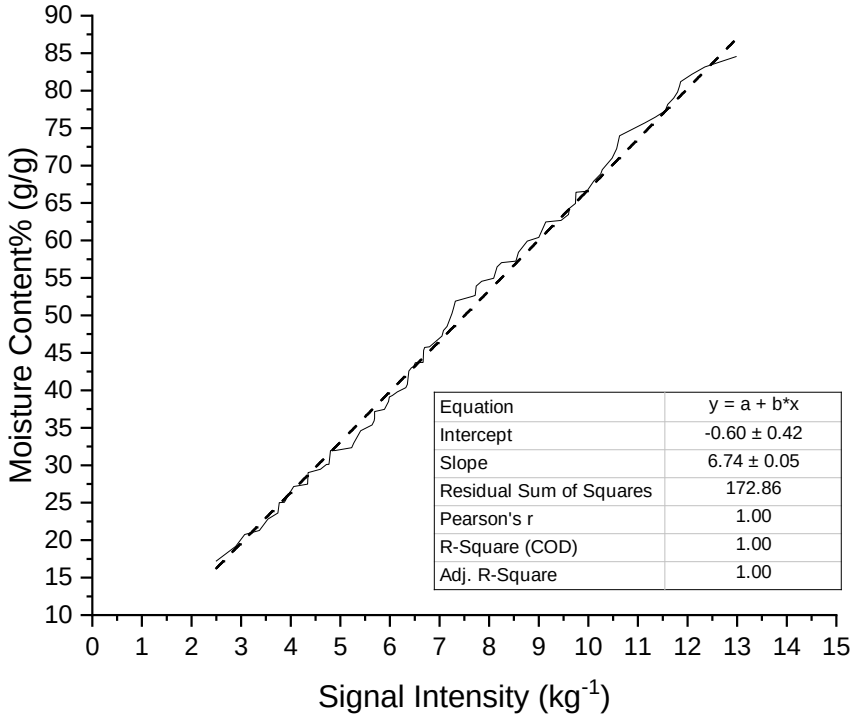

Figure 4.13. Signal intensity and moisture content of apple drying.

Moisture content values obtained as a result of fitting were compared with experimental values and RMSE values were calculated. RMSE values are low in apple drying. The lowest RMSE value was observed at 50°C and r=0 cm and the highest RMSE value was observed at 60°C and r=3 cm. It was concluded that the TD-NMR method can be used to determine the moisture content of apple samples during drying.

Table 4.9. Statistical analysis of TD-NMR signal intensity of apple drying experiment.

	Temperature								
	50°C			**60°C**			**70°C**		
	r=0 (cm)	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**	**r=0 (cm)**	**r=1.5 (cm)**	**r=3 (cm)**
MAE	3.03	3.01	4.32	4.22	4.29	4.62	2.95	2.90	3.79
RMSE	3.60	3.69	4.90	4.75	4.67	4.92	3.33	3.26	4.11
R^2	0.9	0.89	0.9	0.91	0.91	0.91	0.91	0.92	0.92

1Mean absolute error (MAE), root mean square error (RMSE) and R^2 results of apple drying.

Ohgi et al. (2021) reported that the TD-NMR method is usable for the pharmaceutical industry. The TD-NMR signals of the drug mixture prepared at 40 and 5% water to water ratios were measured. Mixtures with high water content had higher T_2 and signal intensity values. In addition, the signal intensity and water ratios were calibrated. RMSE values ranged from 9 to 1.

Castell-Palou et al. (2011) showed that TD-NMR method is suitable for understanding the ripening of cheese. NMR signals and moisture content results were calibrated. The R^2 of the calibration curve was calculated as 0.99.

Schinabeck et al. (2020) reported that NMR method is suitable to measure moisture content of grains. A calibration curve was reported using three different grains with 283 different moisture contents. Linear fitting method was used for calibration. It was determined that a curve suitable for linear fitting and its R^2 was 0.99.

Weiqiao et al. (2018) reported that NMR method is suitable to measure water and oil amount of dairy product. A calibration curve was obtained by using oil and water ratios of dairy product and NMR signal. The R^2 of the calibration curve for ice cream ranged from 0.91 to 0.99. The R^2 of the calibration curve for cheese ranged from 0.75 to 0.95.

4.3 Magnetic Resonance Imaging Results

Magnetic resonance imaging (MRI) provides non-invasive detection and quantitative visualization of water content and water distribution in food. Transverse relaxation time (T_2) provides information about the amount of water and the interaction between water and other macromolecules. MRI images can visualize the spatial distribution of water in food and structural changes during the drying process. Different values of T_2 reflect different amount of water. Higher values of T_2 represent water with higher mobility. A high T_2 value also indicates that the amount of water amount in the food is high.

Since a more homogeneous drying was observed in experiments with chickpeas, MRI measurements were used only for chickpeas. A sample was taken every 20 min for measurement and these samples were filled into test tubes. The signal intensities calculated using the MRI method are the signals of the test tubes. However, it is possible to understand the entire drying process by using the average signal intensities of the test tubes.

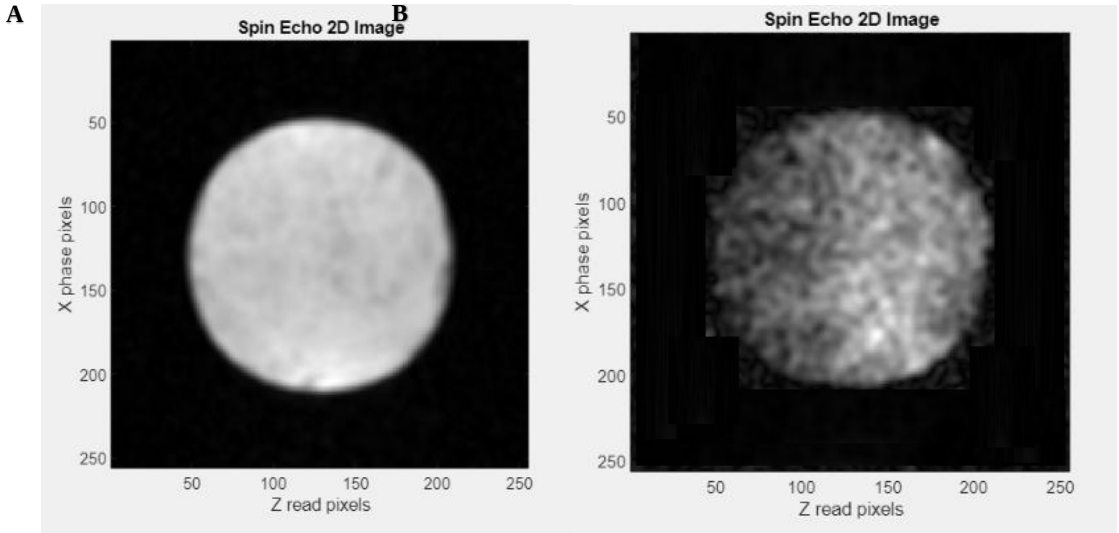

Figure 4.14. Magnetic resonance imaging center of chickpea drying at 50°C

(A represents chickpea drying at time 0 B represents chickpea drying at time 180 min.)

These images consist of 250x250 matrices. In the middle of the images, new 40x40 matrices were created. The aim of this matrix is to focus on the food sample, rather than examining the entire image. Images were compared with each other using all measurements, and a new imaging method was developed using the hundred system. With this method, information was obtained about the drying of chickpeas. Different moisture content was detected for MRI depending on position, temperature and time.

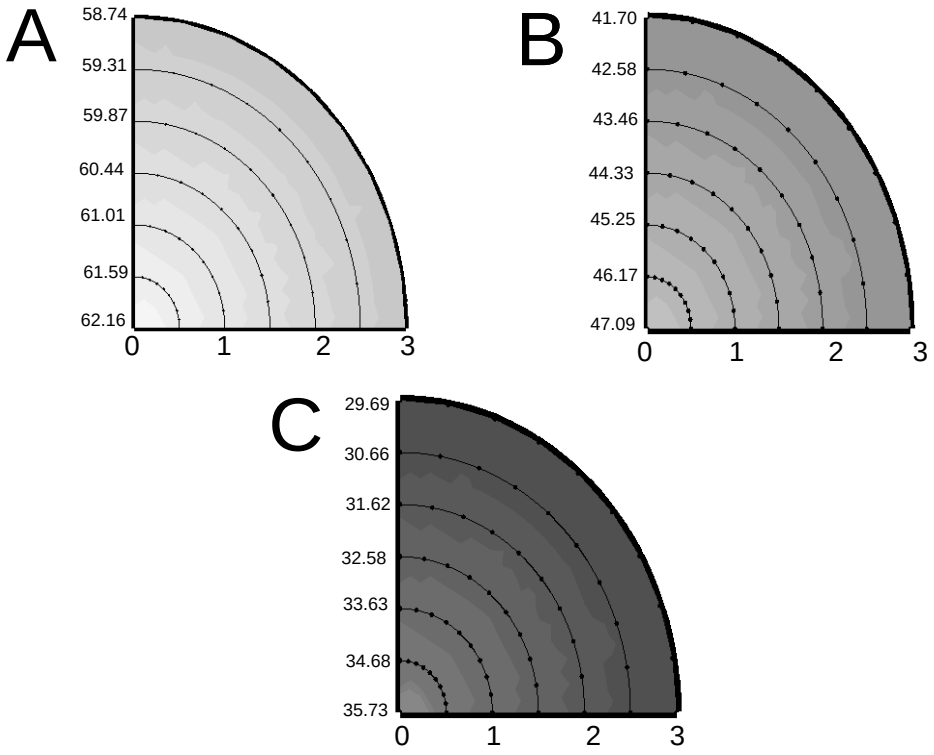

Figure 4.15. Chickpea drying magnetic resonance imaging result at 50°C (A=1 h, B=2 h, C=3 h).

In the chickpea drying experiment, a decrease in the signal intensity of the magnetic resonance imaging method was observed due to the decrease in the moisture content. In addition, spatial moisture content distribution was observed in more detail with the MRI technique. The MRI technique allowed more observation points to be examined. In the drying experiment at 50°C, it was determined that the signal intensity decreased from 79.18±1.25 to 29.69±1.47 kg^{-1}. The lowest signal intensity

value was measured at the corner of the chickpea. As the drying time increased, the moisture content difference between the center and the corner of the chickpea was better understood by the MRI method. Curve fitting was performed using the moisture content and MRI signal intensity data. Calibration became more difficult as the moisture content decreased. However, the R^2 of the calibration curve is 0.96. Thus, it is possible to detect spatial moisture content using the MRI technique.

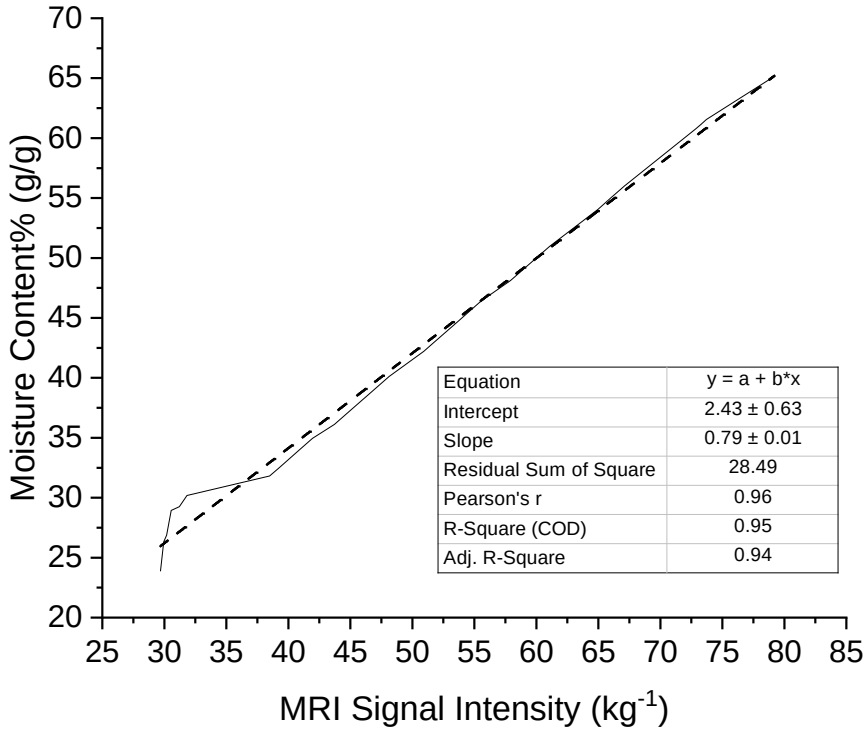

Figure 4.16. MRI signal intensity vs moisture content (%) curve fitting.

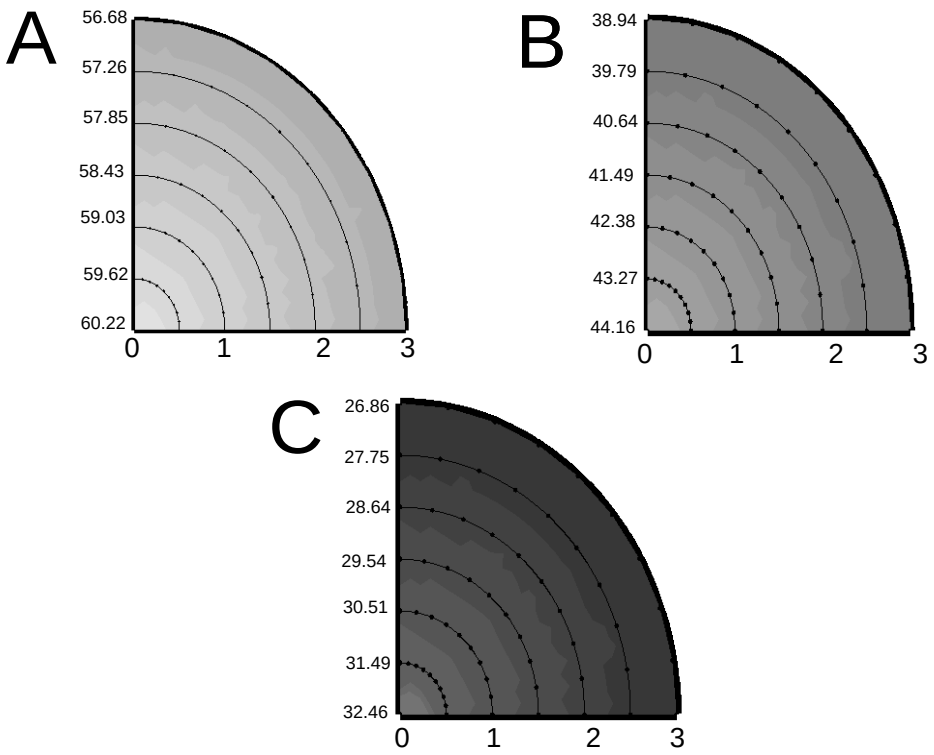

Figure 4.17. Chickpea drying magnetic resonance imaging result at 60°C (A=1 h, B=2 h, C=3 h).

In the drying experiment at 60°C, it was determined that the signal intensity decreased from 79.18±1.25 to 26.86±1.87 kg^{-1}. The lowest signal intensity value was measured at the corner of the chickpea. Curve fitting was performed, and R^2 of the curve was determined as 0.94 at 60°C.

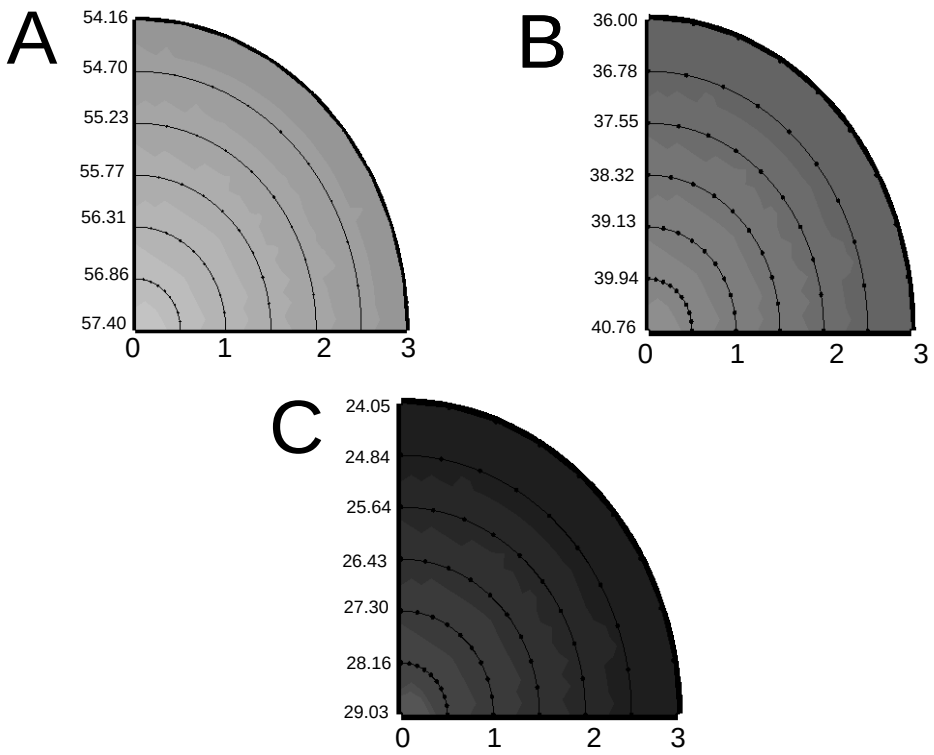

Figure 4.18. Chickpea drying magnetic resonance imaging result at 70°C (A=1 h, B=2 h, C=3 h).

In the drying experiment at 70°C, it was determined that the signal intensity decreased from 79.18±1.25 to 24.05±1.22 kg^{-1}. The lowest signal intensity value was measured at the corner of the chickpea. Curve fitting was performed and R^2 of the curve was determined as 0.94 at 70°C.

Lv et al. (2018) reported that the corn kernel was dried by microwave and vacuum drying method, and the moisture content change was detected by MRI method. Curve fitting was performed using corn kernel moisture content and MRI signal. According to the fitting results, the moisture content and signal data were very close to each other and its R^2 was determined as 0. 991. Hwang & Lin (2004) reported that the rice kernel was dried by oven drying method, and the moisture content change was detected by MRI method. Curve fitting was performed by using the double exponential method and the R^2 of the fitting was 0.997.

CHAPTER 5

CONCLUSION

Chickpea, apple and eggplant drying experiments were carried out at 50-70°C using a rotary tray dryer. The moisture content of the dried foods was measured at 20-minute intervals during drying. Three different techniques were used for moisture measurement. As the first technique, the oven method was used. It is an old and precise method of determining moisture content, but it takes a long time to determine moisture content. The second method was the TD-NMR method. The NMR signal can be effectively separated from the water and solids in the sample because there is a large variation in the magnetic resonance susceptibility of solids and water. In addition, moisture content can be measured in a short time. The third method was the MRI method. It is a method for measuring the moisture content of food using a magnetic field. Spatial moisture content changes in foods during drying were determined using this method. Both TD-NMR and MRI methods were successful in measuring moisture content in the selected foods.

It was determined that the drying temperature and spatial moisture variation content affect the drying time. It was observed that the drying time decreased as the drying temperature increased. The corner of the food dried in a shorter time than the center of the food. In the drying experiments, drying rate was calculated and constant drying rate and falling drying rate were observed. It was determined that the moisture content change depending on the position had an effect as much as the drying temperature. In the drying experiments carried out at high temperatures, it was observed that the corner of the food hardened and crusted as the drying time passed, while the center of the food still remained wet.

Further studies are also needed using other moisture content detection methods. In this way, instead of the oven method, which takes a long time, methods that give precise results in a shorter time can be recommended.

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APPENDICES

A. TD-NMR Results for Drying of Chickpea

At 50 °C

	Time	50 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	260.6	27.66	12.65	0.45	12.18	0.31
	20	194.97	24.53	11.32	0.5	10.75	0.33
	40	156.7	15.1	10.88	0.72	10.21	0.37
	60	139.55	15.05	10.33	0.49	9.62	0.25
	80	117.45	18.56	7.99	0.81	7.33	0.47
	100	101.95	14.65	7.41	0.7	6.72	0.36
	120	88.96	27.68	6.87	0.27	6.14	0.19
	140	69.96	25.82	5.93	0.7	5.14	0.48
	160	57.94	17.9	4.61	0.83	3.88	0.47
	180	48.69	16.25	4.3	0.35	3.5	0.19
r=1.5	0	260.6	27.66	12.65	0.32	12.18	0.23
	20	188.58	24.53	10.51	0.5	9.97	0.33
	40	151.39	15.95	10.1	0.46	9.46	0.24
	60	134.61	21.96	9.63	0.73	8.94	0.46
	80	113.63	26.25	7.31	0.27	6.7	0.18
	100	98.23	27.27	6.73	0.88	6.08	0.61
	120	86.13	18.62	6.23	0.74	5.55	0.43
	140	67.46	27.51	5.41	0.68	4.67	0.48
	160	56.41	15.05	4.16	0.83	3.48	0.55
	180	45.69	13.8	3.81	0.88	3.06	0.58
r=3	0	260.6	27.66	12.65	0.61	12.18	0.42
	20	181.98	24.53	9.7	0.5	9.18	0.33
	40	145.76	18.33	9.31	0.59	8.69	0.34
	60	129.39	15.69	8.91	0.6	8.25	0.32
	80	109.31	22.58	6.62	0.66	6.04	0.42
	100	94.04	15.86	6.04	0.52	5.43	0.28
	120	82.74	15.77	5.58	0.6	4.95	0.32
	140	64.44	21.72	4.87	0.88	4.17	0.56
	160	53.73	10.77	3.66	0.49	3.49	0.31
	180	43.38	13.13	3.34	0.33	3.19	0.22

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 60 °C

	Time	60 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	260.6	27.66	12.65	0.45	12.18	0.31
	20	190.84	24.53	11.2	0.5	10.65	0.33
	40	151.13	21.93	10.74	0.52	10.06	0.33
	60	133.91	11.42	10.19	1.04	9.45	0.43
	80	112.48	12.59	7.84	0.48	7.17	0.22
	100	96.2	9.7	7.23	0.91	6.52	0.33
	120	83.6	26.79	6.7	0.87	5.94	0.6
	140	65.14	13.19	5.76	0.82	4.94	0.38
	160	53.53	15.98	4.43	0.59	3.68	0.32
	180	44.88	11.35	4.14	0.74	3.32	0.31
r=1.5	0	260.6	12.13	12.65	0.53	12.18	0.23
	20	183.32	24.53	10.39	0.5	9.84	0.33
	40	146.03	15.01	9.96	0.89	9.3	0.46
	60	129.18	14.41	9.48	0.89	8.78	0.45
	80	108.82	13.58	7.17	0.58	6.54	0.28
	100	92.69	15.66	6.56	0.61	5.89	0.32
	120	80.95	26.75	6.07	0.94	5.36	0.65
	140	62.8	19.86	5.24	0.88	4.47	0.53
	160	52.11	20.04	3.98	0.81	3.29	0.49
	180	42.12	19.7	3.66	0.37	2.88	0.22
r=3	0	260.6	21.28	12.65	0.25	12.18	0.15
	20	176.92	24.53	9.58	0.5	9.05	0.33
	40	140.6	26.67	9.17	0.94	8.54	0.65
	60	124.16	13.11	8.77	0.76	8.09	0.35
	80	104.67	19.62	6.48	0.18	5.89	0.11
	100	88.75	21.74	5.87	0.77	5.24	0.49
	120	77.75	19.49	5.42	0.83	4.76	0.49
	140	59.98	17.31	4.7	0.84	3.98	0.47
	160	49.64	18.24	3.33	0.3	3.04	0.21
	180	39.98	10.51	3.05	0.15	2.65	0.09

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 70 °C

	Time	70 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	260.6	27.66	12.65	0.45	12.18	0.31
	20	184.25	24.53	11.08	0.5	10.5	0.33
	40	145.76	20.67	10.61	0.54	9.9	0.33
	60	128.51	13.98	10.05	0.74	9.3	0.36
	80	107.72	20.57	7.7	0.92	7.02	0.57
	100	90.77	17.92	7.07	0.37	6.33	0.21
	120	78.58	16.2	6.54	0.19	5.76	0.1
	140	60.64	13.9	5.6	0.67	4.75	0.33
	160	49.46	22.2	4.27	0.46	3.49	0.29
	180	41.37	15.75	4	0.45	3.14	0.24
r=1.5	0	260.6	13.54	12.65	0.16	12.18	0.08
	20	178.19	24.53	10.27	0.5	9.71	0.33
	40	140.83	23.64	9.83	0.55	9.16	0.36
	60	123.98	20.55	9.35	0.27	8.62	0.16
	80	104.2	26.57	7.03	0.25	6.38	0.17
	100	87.45	14.07	6.39	0.67	5.7	0.33
	120	76.07	23.53	5.91	0.46	5.18	0.3
	140	58.47	22.97	5.09	0.19	4.29	0.12
	160	48.15	15.16	3.82	0.59	3.11	0.3
	180	38.82	21.39	3.51	0.26	2.72	0.16
r=3	0	260.6	15.28	12.65	0.2	12.18	0.1
	20	171.99	24.53	9.46	0.5	8.93	0.33
	40	135.61	24.44	9.04	0.28	8.4	0.18
	60	119.17	24.43	8.63	0.51	7.94	0.34
	80	100.24	25.24	6.34	0.86	5.74	0.58
	100	83.75	15.08	5.71	0.57	5.07	0.29
	120	73.08	16.26	5.27	0.77	4.59	0.42
	140	55.84	14.09	4.55	0.35	3.8	0.17
	160	45.86	14.37	2.85	0.48	2.68	0.24
	180	36.85	15.4	2.48	0.57	2.33	0.3

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

B. TD-NMR Results for Drying of Eggplant

At 50 °C

		Drying Temperature					
	Time	50 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	374.67	25.82	13.89	0.53	13.53	0.36
	40	302.06	15.89	13.12	0.76	12.69	0.41
	60	266.91	15.84	12.35	0.52	11.89	0.28
	80	230.21	19.54	10.01	0.85	9.59	0.51
	100	211.64	15.42	9.51	0.74	9.07	0.39
	120	194.55	29.14	9	0.28	8.55	0.2
	140	172.21	27.18	8.27	0.74	7.8	0.51
	160	158.7	18.84	7.18	0.87	6.74	0.51
	180	150.69	17.11	7.07	0.37	6.62	0.21
r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	367.4	25.82	13.17	0.47	12.81	0.32
	40	288.82	16.79	12.27	0.48	11.85	0.26
	60	257.07	23.12	11.62	0.77	11.18	0.5
	80	230.21	27.63	9.5	0.28	9.09	0.19
	100	211.64	28.71	8.99	0.93	8.58	0.66
	120	194.55	19.6	8.5	0.78	8.07	0.47
	140	169.34	28.96	7.8	0.72	7.35	0.51
	160	153.24	26.37	6.68	0.87	6.26	0.6
	180	135.99	25.05	6.32	0.47	5.87	0.32
r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	360.13	25.82	12.44	0.53	12.1	0.36
	40	278.91	19.29	11.48	0.62	11.07	0.37
	60	243.94	16.52	10.82	0.63	10.38	0.34
	80	205.09	23.77	8.41	0.69	8.01	0.45
	100	183.74	16.69	7.83	0.55	7.41	0.3
	120	163.83	16.6	7.28	0.63	6.84	0.34
	140	137.93	22.86	6.59	0.93	6.12	0.6
	160	123.31	21.86	5.47	0.52	5.05	0.33
	180	116.49	24.35	5.41	0.35	4.96	0.23

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 60 °C

		Drying Temperature					
		60 °C					
	Time	T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	367.4	25.82	13.77	0.53	13.4	0.36
	40	292.14	23.08	12.93	0.55	12.5	0.36
	60	250.53	12.02	12.04	1.09	11.57	0.47
	80	208.24	13.25	9.53	0.51	9.09	0.24
	100	183.74	10.21	8.89	0.96	8.42	0.36
	120	160.75	28.2	8.23	0.92	7.74	0.65
	140	129.38	13.88	7.19	0.86	6.66	0.42
	160	109.69	16.82	5.83	0.62	5.32	0.34
	180	98.06	11.95	5.57	0.78	5.03	0.34
r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	360.13	29.12	13.04	0.47	12.68	0.33
	40	278.91	15.8	12.08	0.94	11.65	0.5
	60	234.1	15.17	11.17	0.94	10.7	0.49
	80	201.94	14.29	8.86	0.61	8.44	0.3
	100	177.56	16.48	8.21	0.64	7.76	0.35
	120	154.58	28.16	7.57	0.99	7.1	0.69
	140	123.65	20.91	6.63	0.93	6.12	0.58
	160	101.5	21.09	5.22	0.85	4.73	0.53
	180	87.54	20.74	4.91	0.47	4.38	0.29
r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	352.9	29.12	12.31	0.53	11.97	0.38
	40	268.96	28.07	11.28	0.99	10.87	0.69
	60	230.81	13.8	10.56	0.8	10.11	0.39
	80	195.68	20.65	8.2	0.19	7.79	0.12
	100	168.24	22.88	7.46	0.81	7.03	0.52
	120	142.29	20.52	6.76	0.87	6.3	0.53
	140	109.36	18.22	5.84	0.88	5.33	0.51
	160	87.88	29.73	4.46	0.32	3.98	0.23
	180	77.02	21.59	4.24	0.16	3.72	0.1

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 70 °C

		Drying Temperature					
	Time	70 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	360.13	25.82	13.65	0.53	13.27	0.36
	40	282.23	21.76	12.74	0.57	12.3	0.36
	60	237.36	14.72	11.79	0.78	11.3	0.4
	80	192.53	21.65	9.19	0.97	8.73	0.61
	100	165.17	18.86	8.47	0.39	7.98	0.23
	120	139.24	17.05	7.75	0.2	7.21	0.11
	140	106.49	14.63	6.62	0.71	6.03	0.36
	160	85.18	23.37	5.15	0.48	4.58	0.31
	180	74.39	16.58	4.89	0.47	4.27	0.26
r=1.5	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	352.9	25.82	12.91	0.53	12.55	0.36
	40	268.96	24.88	11.88	0.58	11.45	0.39
	60	220.97	21.63	10.91	0.28	10.43	0.18
	80	176.81	27.97	8.3	0.26	7.85	0.18
	100	149.67	14.81	7.58	0.71	7.09	0.36
	120	123.86	24.77	6.86	0.48	6.33	0.32
	140	92.21	24.18	5.83	0.2	5.23	0.13
	160	71.57	15.96	4.38	0.62	3.81	0.33
	180	58.62	22.52	4.06	0.27	3.43	0.17
r=3	0	437.75	29.12	14.75	0.47	14.42	0.33
	20	345.62	25.82	12.18	0.53	11.83	0.36
	40	259.04	25.73	11.08	0.29	10.66	0.2
	60	214.38	25.72	10.23	0.54	9.76	0.37
	80	170.51	26.57	7.62	0.9	7.18	0.62
	100	140.38	15.87	6.81	0.6	6.34	0.32
	120	111.57	17.12	6.03	0.81	5.51	0.45
	140	77.95	14.83	5.02	0.37	4.42	0.19
	160	55.22	15.13	3.52	0.51	2.93	0.26
	180	45.47	16.21	3.3	0.6	2.65	0.32

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

C. TD-NMR Results for Drying of Apple

At 50 °C

		Drying Temperature					
	Time	50 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	415.85	17.2	12.65	0.31	12.35	0.17
	40	357.25	28.39	11.46	1.1	11.14	0.77
	60	319.55	23.05	10.61	0.49	10.28	0.32
	80	290.2	12.26	8.89	1.29	8.59	0.57
	100	273.45	26.6	8.46	0.69	8.16	0.47
	120	256.7	17.18	8.02	0.22	7.72	0.12
	140	244.15	11.46	7.45	0.44	7.15	0.18
	160	235.75	16.27	6.71	0.21	6.43	0.11
	180	231.55	12.7	6.6	0.64	6.32	0.29
r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	395.05	19.27	12.02	1.25	11.72	0.74
	40	339.4	23.13	10.89	1.24	10.57	0.8
	60	303.55	12.6	10.08	1.15	9.75	0.52
	80	275.7	29.54	8.39	0.68	8.09	0.48
	100	259.8	12.57	7.98	0.87	7.67	0.39
	120	243.85	18.89	7.56	0.53	7.25	0.31
	140	231.95	27.93	7	1.16	6.7	0.81
	160	223.95	11.84	6.26	0.6	5.99	0.26
	180	219.95	13.08	6.16	0.58	5.89	0.27
r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	407.5	27.04	12.15	0.89	11.86	0.61
	40	340.45	24.75	10.79	0.62	10.48	0.41
	60	302.75	23.25	9.95	0.87	9.62	0.57
	80	269.25	28.33	8.15	0.8	7.85	0.56
	100	248.3	23.98	7.63	1.22	7.32	0.8
	120	227.35	19.17	7.11	1.3	6.8	0.77
	140	210.6	10.02	6.45	0.21	6.15	0.08
	160	202.25	16.4	5.71	0.31	5.43	0.17
	180	202.25	15.04	5.69	0.25	5.41	0.13

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 60 °C

		Drying Temperature					
	Time	60 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	403.3	25.08	12.4	0.53	12.09	0.36
	40	332.1	11.17	10.95	0.91	10.63	0.37
	60	286	19.32	9.94	0.63	9.6	0.38
	80	248.3	30	8.06	0.16	7.74	0.11
	100	223.2	22.24	7.45	1.07	7.13	0.68
	120	198.05	16.69	6.85	0.91	6.51	0.5
	140	172.9	12.65	6.03	0.77	5.69	0.35
	160	156.15	19.37	5.11	0.97	4.8	0.58
	180	147.8	15.75	4.93	0.37	4.6	0.2
r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	399.1	23.19	12.1	0.75	11.8	0.49
	40	323.7	23.19	10.57	1.28	10.25	0.83
	60	273.45	17.26	9.48	0.73	9.14	0.41
	80	235.75	12	7.6	0.64	7.28	0.28
	100	210.6	17.42	6.99	1.07	6.67	0.6
	120	185.5	11.86	6.39	0.38	6.05	0.16
	140	160.35	18.03	5.57	0.78	5.23	0.45
	160	143.6	13.16	4.65	0.28	4.34	0.13
	180	131.05	13.15	4.38	0.5	4.06	0.23
r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	394.95	16.52	11.9	0.43	11.6	0.23
	40	315.35	13.38	10.29	0.55	9.97	0.26
	60	260.9	27.43	9.11	0.64	8.77	0.44
	80	231.55	16.18	7.39	0.53	7.08	0.29
	100	202.25	21.89	6.71	1.26	6.38	0.8
	120	172.9	16.87	6.02	0.76	5.68	0.42
	140	143.6	19.49	5.11	0.98	4.77	0.59
	160	131.05	19.37	4.28	0.73	3.97	0.44
	180	122.65	13.46	4.09	0.67	3.77	0.32

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

At 70 °C

		Drying Temperature					
	Time	70 °C					
		T_2(ms)		M_0(kg^{-1})		SI(kg^{-1})	
		Value	SE	Value	SE	Value	SE
r=0	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	390.75	18.46	12.15	0.17	11.84	0.1
	40	306.95	27.26	10.45	0.56	10.11	0.39
	60	256.7	17.67	9.35	0.43	9	0.24
	80	214.8	22.91	7.39	0.94	7.05	0.61
	100	185.5	21.33	6.7	0.68	6.35	0.43
	120	156.15	27.44	6.01	0.93	5.64	0.65
	140	126.85	27.8	5.11	1.15	4.72	0.8
	160	105.9	19.81	4.11	1.23	3.74	0.74
	180	97.5	12.88	3.92	0.33	3.54	0.15
r=1.5	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	386.55	28.55	11.85	1.08	11.55	0.76
	40	298.6	22.95	10.07	0.67	9.74	0.43
	60	244.15	19.28	8.89	0.32	8.54	0.19
	80	206.45	19.17	7.01	1.24	6.68	0.74
	100	177.1	17.08	6.32	0.19	5.97	0.11
	120	147.8	20.21	5.64	1.18	5.27	0.72
	140	118.45	23.25	4.73	1.24	4.35	0.81
	160	97.5	21.56	3.73	0.98	3.37	0.62
	180	84.95	12.86	3.46	0.53	3.07	0.24
r=3	0	422.75	27.24	13.3	0.98	12.98	0.68
	20	382.35	23.9	11.65	0.19	11.35	0.13
	40	290.2	24.54	9.78	0.47	9.45	0.31
	60	235.75	18.51	8.61	0.58	8.25	0.34
	80	202.25	19.46	6.81	0.6	6.48	0.36
	100	168.75	21.14	6.04	0.31	5.69	0.19
	120	135.2	22.29	5.26	0.89	4.89	0.57
	140	101.7	22.58	4.27	0.69	3.87	0.44
	160	80.75	10.76	3.28	0.16	2.89	0.06
	180	64	19.39	2.92	0.25	2.5	0.15

T_2 Transverse Relaxation Time, M_0 Proton Intensity, SI Signal Intensity, SE Standard Error

D. Chickpea TD-NMR Signal Intensity vs Moisture% Fitting

Parameters

		Value	Standard Error	t-Value	Prob>|t|
Moisture Content%	Intercept	10.14	0.37	27.71	0.00
	Slope	4.66	0.05	94.97	0.00

Slope is significantly different from zero (See ANOVA Table).
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Moisture Content%
Number of Points	90
Degrees of Freedom	88
Residual Sum of Squares	163.07
Pearson's r	1.00
R-Square (COD)	0.99
Adj. R-Square	0.99

Summary

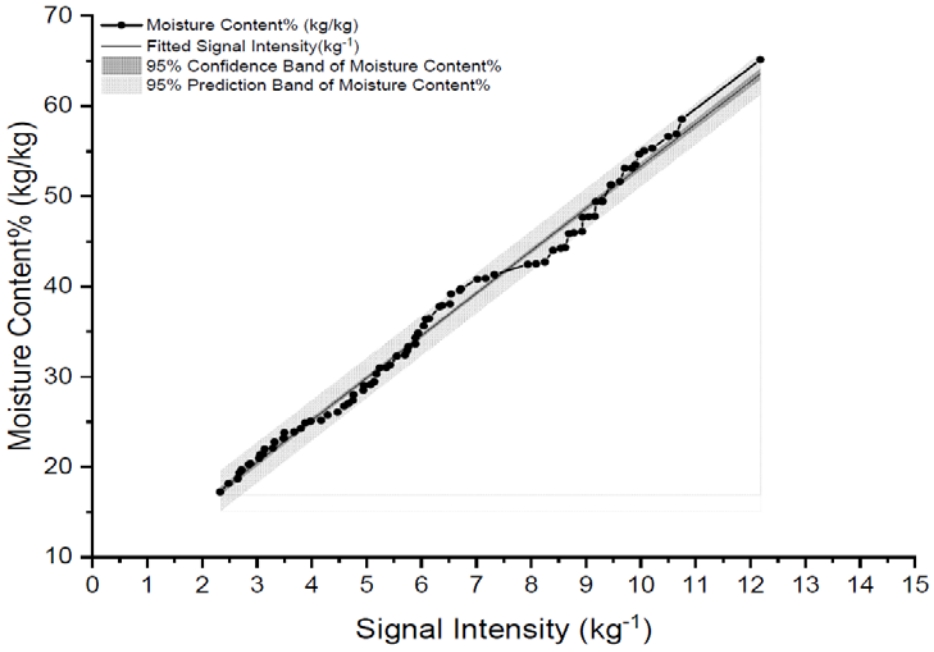
	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
Moisture Content%	10.14	0.37	4.66	0.05	0.99

ANOVA

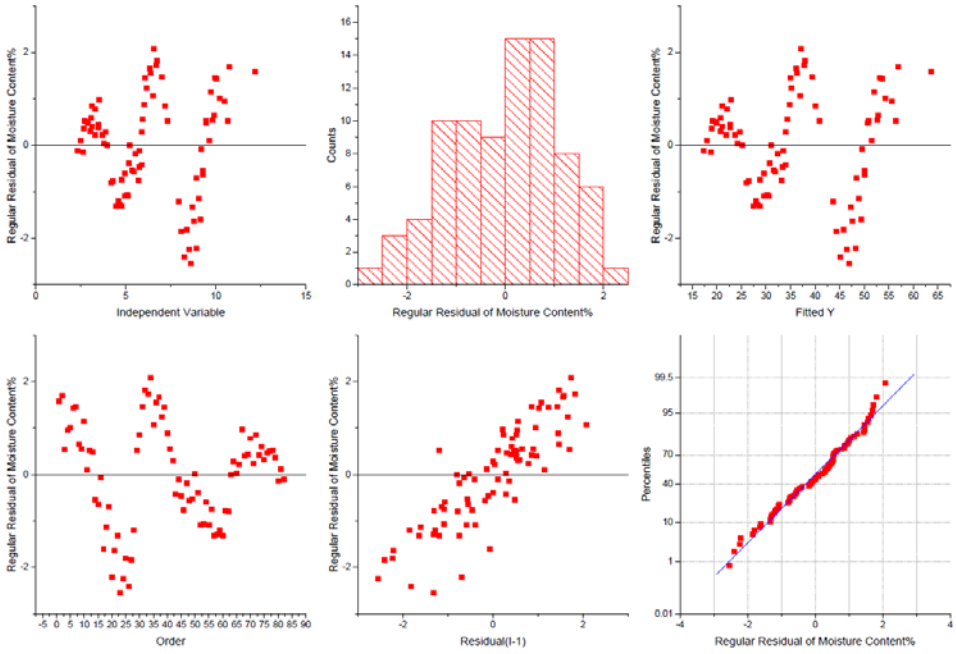
		DF	Sum of Squares	Mean Square	F Value	Prob>F
Moisture%	Model	1	16712.42	16712.42	9018.79	0.00
	Error	88	163.07	1.85		
	Total	89	16875.49			

At the 0.05 level, the slope is significantly different from zero.

Fitted Curves Plot



Residual Plot



E. Apple TD-NMR Signal Intensity vs Moisture% Fitting

Parameters

		Value	Standard Error	t-Value	Prob>|t|
Moisture%	Intercept	-0.60	0.42	-1.44	0.15
	Slope	6.74	0.05	136.10	4.13E-104

Slope is significantly different from zero (See ANOVA Table).
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Moisture%
Number of Points	90
Degrees of Freedom	88
Residual Sum of Squares	172.86
Pearson's r	1.00
R-Square (COD)	1.00
Adj. R-Square	1.00

Summary

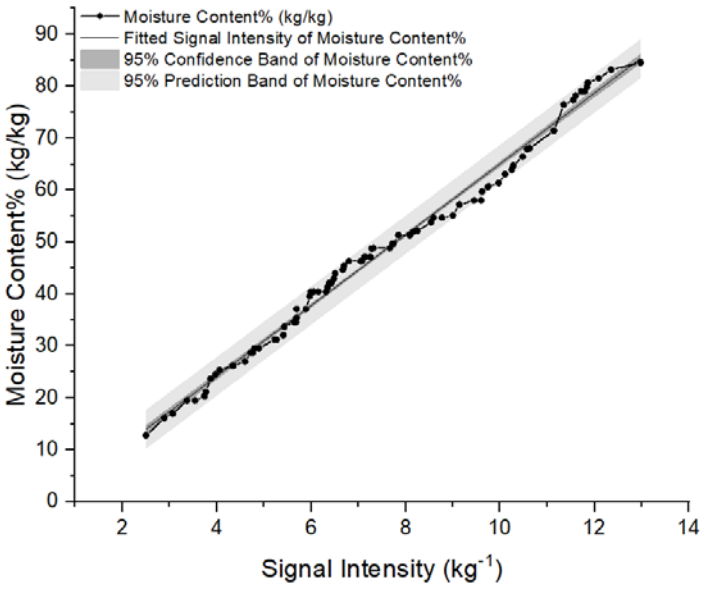
	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
Moisture%	-0.60	0.42	6.74	0.05	1.00

ANOVA

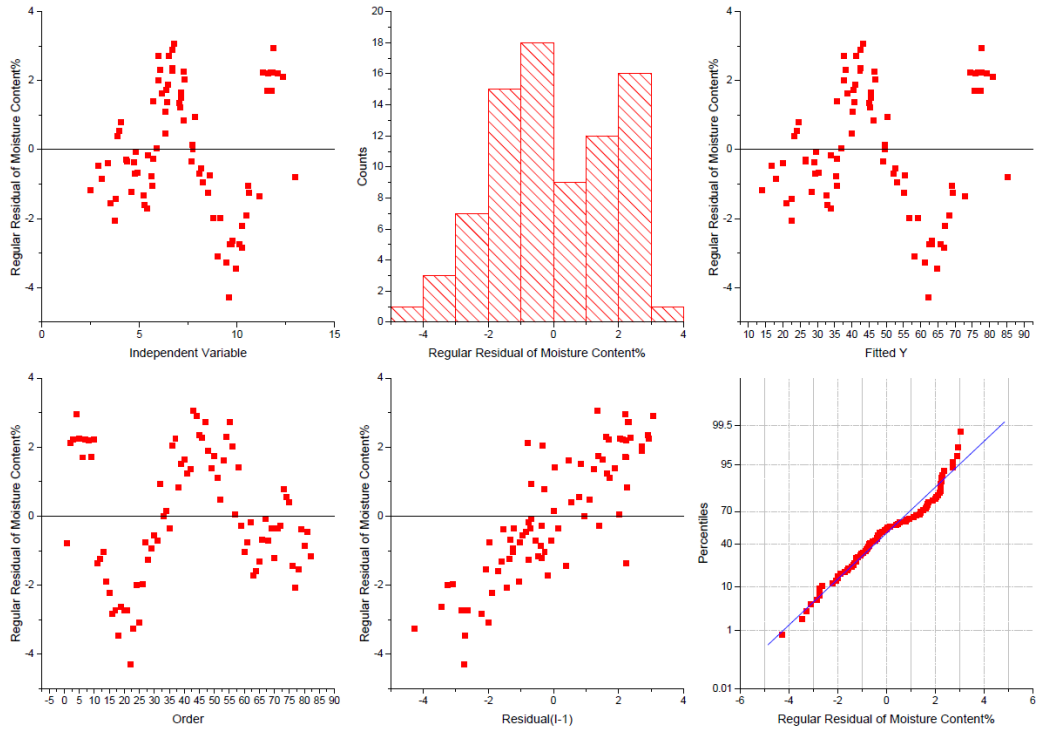
		DF	Sum of Squares	Mean Square	F Value	Prob>F
Moisture%	Model	1.00	36385.16	36385.16	18522.58	4.14E-104
	Error	88.00	172.86	1.96		
	Total	89.00	36558.03			

At the 0.05 level, the slope is significantly different from zero.

Fitted Curves Plot



Residual Plot



F. Eggplant TD-NMR Signal Intensity vs Moisture% Fitting

Parameters

		Value	Standard Error	t-Value	Prob>|t|
Moisture%	Intercept	4.23	0.49	8.56	0.00
	Slope	5.95	0.05	113.60	0.00

Slope is significantly different from zero (See ANOVA Table).
Standard Error was scaled with square root of reduced Chi-Sqr.

Statistics

	Moisture%
Number of Points	90
Degrees of Freedom	88
Residual Sum of Squares	241.54
Pearson's r	1.00
R-Square (COD)	0.99
Adj. R-Square	0.99

Summary

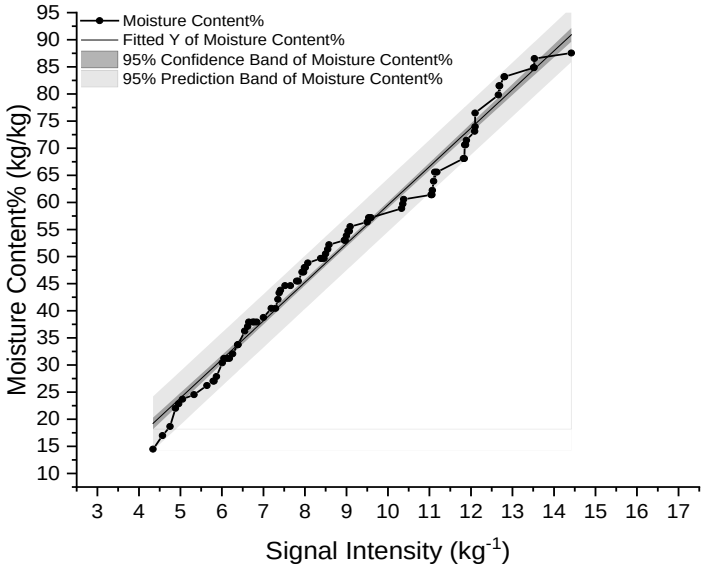
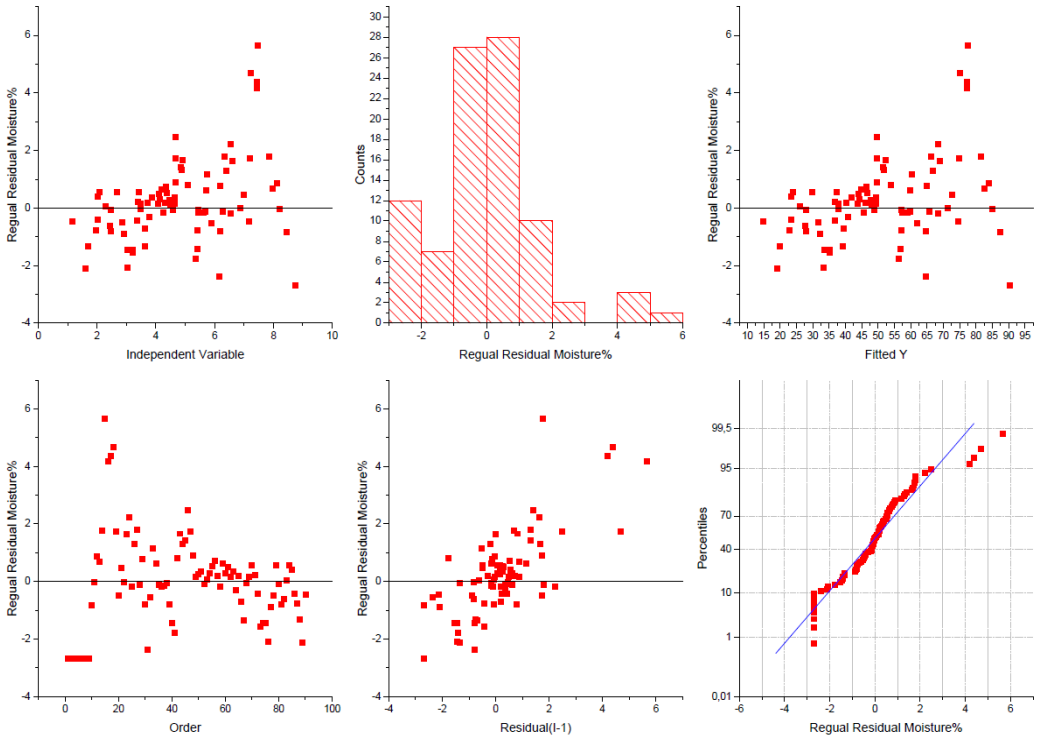
	Intercept		Slope		Statistics
	Value	Standard Error	Value	Standard Error	Adj. R-Square
Moisture%	4.23	0.49	5.95	0.05	0.99

ANOVA

		DF	Sum of Squares	Mean Square	F Value	Prob>F
Moisture%	Model	1	35419.47	35419.47	12904.31	0.00
	Error	88	241.54	2.74		
	Total	89	35661.01			

At the 0.05 level, the slope is significantly different from zero.

Fitted Curves Plot



Residual Plot