Experimental investigation on black pepper drying in a hot air cabinet dryer for optimized energy performance

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Degree of Master of Engineering

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ABSTRACT

Open sun drying is the widely used passive method for black pepper drying, but due to its limitations such as unavailability on rainy days, lack of controllability, degradation of food quality, loss of volatile oil, and improper drying, the active dryers have become more popular than the open sun drying method. Among these active dryers, tray dryers are extremely popular in medium and small-scale black pepper processing industries because they are small in size, simple in design and lower capital cost comparative to other dryers. It is extremely important to identify the optimum drying temperature and the hot air velocity for black pepper drying process on a convective tray dryer to minimize the total energy while improving the quality of the black pepper. The drying properties of black pepper were examined in a convective thermal tray dryer during this investigation. In house built experimental setup was used to understand the variations of moisture ratio (MR) during the drying. The experiments were carried out in different temperatures of 50 °C, 55 °C and 60 °C and, for three different air speeds of 0.4ms^{-1}, 0.8 ms^{-1} and 1.2 ms^{-1}. The observed experimental results were fitted with the existing drying models. Model coefficients and constants were evaluated by using the MS Excel software. The Logarithmic model was discovered as the best drying model to explore the black pepper drying on a convective hot air tray dryer with an average RMSD (root mean square deviation) of 0.0140. The total amount of time required to decrease the moisture content (MC) to 12% (minimum secure storage MC) in dry basis under various drying settings were computed using the logarithmic model equation. The total drying energy required to dry 1 kg of raw black pepper for different drying conditions was calculated and, a surface plot of total drying energy against temperature and air speed was generated. Based on the contours of the surface plot, the drying conditions which minimize the total drying energy were determined.

Keywords: Black Pepper, Drying models, Energy optimization, Tray drying

PUBLICATIONS

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DECLARATION

I declare that this is my own work, and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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The above candidate has carried out research for the master's Thesis under my supervision

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Dr. Wijewardane M.A

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RH	Relative Humidity
DB	Dry Basis
WB	Wet Basis
MC	Moisture Content
MR	Moisture Ratio
DM	Drying Model

CHAPTER 1

1. INTRODUCTION

1.1 Food drying

Food drying is a process that removes moisture from food material by evaporating water into the vapor phase. The primary goal of food drying is preservation, and it is the oldest food preservation technique used by the people. Even at present, the main food preservation method is drying. Most of the agricultural food products are seasonal. During the peak-season, they are abundantly available in bulk quantities, and during the off-season, they are not available. Raw agricultural crops contain higher amount of moisture and hence, unprocessed post-harvested crops can be easily perishable and cannot be stored at normal atmospheric conditions in Sri Lanka.

One of the most effective approaches for conserving agricultural products is drying, crops and some animal food products, as it slows down the rate of growth of microorganisms by removing moisture that is required for their activities. Many different foods that are preserved and prepared by drying some of them are, seeds, grain, spices, herbs, fruit, meats, and vegetables. Moreover, drying reduces the food's bulk weight and volume, which may lower the handling, transport, and storage costs. Food drying also alters the taste of the food and provides a unique taste.

1.2 History of food drying

Open sun drying is the main technique used by ancient people to preserve their food products. Even at present, the main food drying method is open sun drying. The amount of energy from the sun is highly dependent on environmental factors and available only in the daytime. Also, it highly fluctuates and intermittent during the time of day, month of the year and latitude of the location. therefore, scheduled, and continuous drying is impossible with solar energy. To overcome these issues the artificial drying techniques are used. Removal of excess moisture by artificial techniques is called artificial drying. Smoke drying is the oldest artificial drying technique used by ancient people. Hot air drying, dielectric drying, fluidized bed drying, infrared drying, and microwave drying are the popular examples for modern artificial drying techniques.

Hot air dryers are the most commonly used artificial dryers (85%) in the food industry today [1]. These dryers use hot air as the drying medium to provide heat for evaporation of water and to take evaporated water beyond from the food being drying. Due to the higher latent energy of evaporation of water and poor thermal energy transfer rate, hot air drying is an extremely energy-intensive operation [1]. The typical specific heat energy utilization of practical hot-air grain dryers ranges from 4–8 MJ/kg [2].

1.3 Black pepper (Piper Nigrum) Drying

Black pepper is one of the main spices used in the world, so it names the "King of the Spice". Black pepper is a tropical plant in the family of Piperaceae and it is native to tropical countries. The world's top black pepper producers include Ethiopia, Vietnam, Brazil, Indonesia, India, and China [3], [4].

The mature black pepper berries are harvested and dried to reduce the moisture for safe storage. Raw black pepper berries content around 65% moisture (wet basis) [5] and it must be reduced up to 12 % (dry basis) [6] for safe storage purpose. Sun-drying is the most commonly used approach for black pepper drying in tropical region of countries. Sun drying extremely rely on the weather and climate conditions, time of the day, month of the day and latitude of the location. Moreover, the amount of heat received by the solar irradiation is difficult to control. Therefore, it may cause the degradation of food quality, loss of volatile oil (volatile organic components – VOC), and or uneven drying. Artificial drying techniques are used to overcome the drawbacks of open sun drying. Tray drying, fluidized bed, and spouted bed drying are the commonly used artificial drying technique for black pepper drying in the industry [6]. Among these artificial dryers, tray dryers are extremely popular in medium and small-scale black pepper processing industries as they are small in size, simple in design, and lower initial cost comparative to other dryers.

1.4 Tray dryers for Black Pepper Drying

Tray dryers are categorized under the hot air dryers. They classified as batch-type dryers and their batch drying time may vary around 2-12 hours depending on the type of material being dried and other drying parameters. Trays are used to keep the food being dried. Figure 1.1 shows a typical tray dryer uses in industry.

Figure 1.1 - Tray dryer

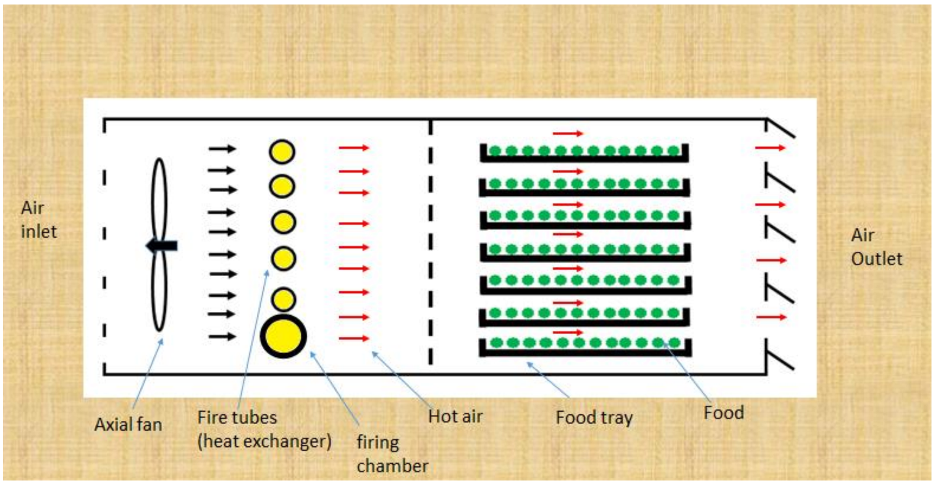

Figure 1.2 - Layout of the cabinet type tray dryer

As illustrated in the Figure 1.2, during the operation of the tray dryer, the atmospheric air is drawn into the dryer by an axial fan, and it passes through the fire tube heat exchanger to heat up. Heated air is forced to flow over the food trays by the axial fan. This hot air flows over the food on the trays and removes moisture from the food loaded on the trays. Most of the tray dryers are operated on biomass, diesel, kerosene, or furnace oil as the fuel.

1.4.1 Energy utilisation in tray drying

The total energy for tray drying is obtained by adding heat required to produce the hot air ($E_{thermal}$) and electrical energy ($E_{mechanical}$) to drive the fans to produce the momentum for hot air flow. That is given by the Equation 1.1.

$$E_{Total} = E_{thermal} + E_{mechanical} \qquad 1.1$$

However, the amount of electrical energy required to drive the fans are very small compared to thermal energy required for drying process. Typically, tray dryers consume about 5% electrical energy and about 95% thermal energy (heat) as shown in the Figure 1.3 [7].

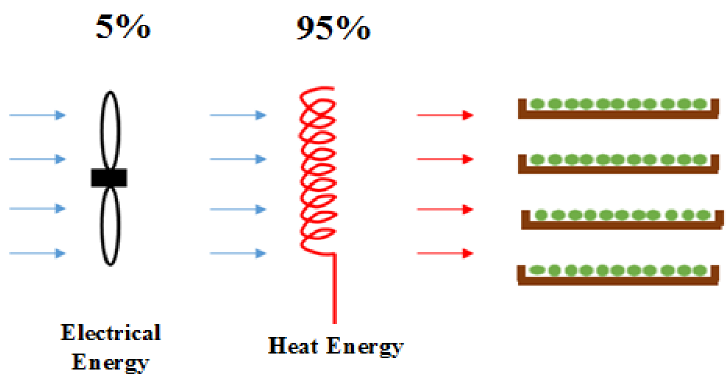

Figure 1.3 - Illustrative diagram of energy utilisation in tray drying

1.5 Problem statement

Drying using hot air consumes a lot of energy. because of the higher latent energy of vaporization of water (2,400 kJ/kg) and poor convection energy transfer rates through air [1]. Most of the freshly harvested crops contain over 50% of water in raw condition and for black pepper that is about 65%. Approximately 2.7 MJ of heat is required to produce 1 kg of dried black pepper (12% of dry basis) from the raw black pepper (65% of the water on a wet basis) [3]. However, industrial tray dryers consume around 100 MJ of energy to produce 1 kg of dried black pepper [3], which is subjected to be varied depending on the drying parameters, resulting very poor efficiencies varies from 1-5%. Moreover, operating the tray dryers with incorrect settings may lead to higher energy loss. By selecting the suitable drying parameters, the total drying energy can be reduced and minimized. This study has been designed to establish the optimum operating parameters of tray dryers use for black pepper drying.

1.5.1 Aim

To improve the energy efficiency of cabinet type tray dryers used for black pepper drying process.

1.5.2 Objectives

1. Recognized the key parameters which govern the drying energy.
2. Design and fabrication of an experimental apparatus for black pepper drying.
3. Identify the most appropriate thin layer drying model for black pepper drying on a tray dryer.
4. Identify the optimum operating temperature and airflow velocity for black paper drying on a tray dryer

1.5.3 Methodology

- Conducting the literature review.
- Design and fabrication of a tray dryer experimental setup.
- Conducting the drying experiments for black pepper by varying the heated air temperature and speed.
- Identify the most appropriate thin layer drying model (DM) for black pepper drying on tray dryer.
- Develop the 3D surface of energy against the heated air velocity and drying temperature.
- Obtaining the drying energy equation as the function of heated air temperature and velocity
- Identify the optimum operating temperature and airflow velocity for black paper drying on the tray dryer.

1.5.3 Scope

The Scope of this analysis is limited to black pepper drying in tray dryers. The response of heated air temperature and air speed on total drying energy were experimented with and examined. The designed parameters of the dryer were assumed to be constant in this study. Experimental data were generated by the tray dryer experimental setup which has multiple trays with one inch gap between them. The length of the each tray is two feet. The data from the experiments were fitted with six popular DMs which are developed and used by various researchers. Degradation of food quality and loss of volatile oil according to the process parameters were not considered in this study.

1.5.4 Outcomes of the study

1. Obtained the best fit thin layer DM for black pepper drying in a tray dryer.
2. Derived the total drying energy consumption as a function of the temperature and speed of the heated air.
3. Obtained the optimum temperature and velocity for the hot air, which minimizes the total drying energy in black pepper drying in tray dryer.

1.5.5 Outline of the study

The First Chapter of the thesis provides an overview for the thesis, highlighting the background, aim, objectives and methodology. Chapter Two of the thesis highlights the food drying processes use for preservation of agricultural products. Chapter 2 also goes through the fundamental theories relate to food drying and classification of food dryers. Chapter 3 describes the research procedure of the study. In addition, it describes the design, fabrication, and testing procedures of the experimental program. The results of the experimental study were explained in Chapter 4 and Chapter 5 includes the conclusions of this study.

CHAPTER 2

2. REVIEW OF THE LITRATURE

2.1 Types of water in food material

The MC of a food refers to how much water is present in it, and it is the governing factor to the growth of the microorganisms which perish the food. By creating a moisture free environment, the growth of microorganisms can be retarded. The water contains in the food are of three forms and are, free water, adsorbed water, and bound water.

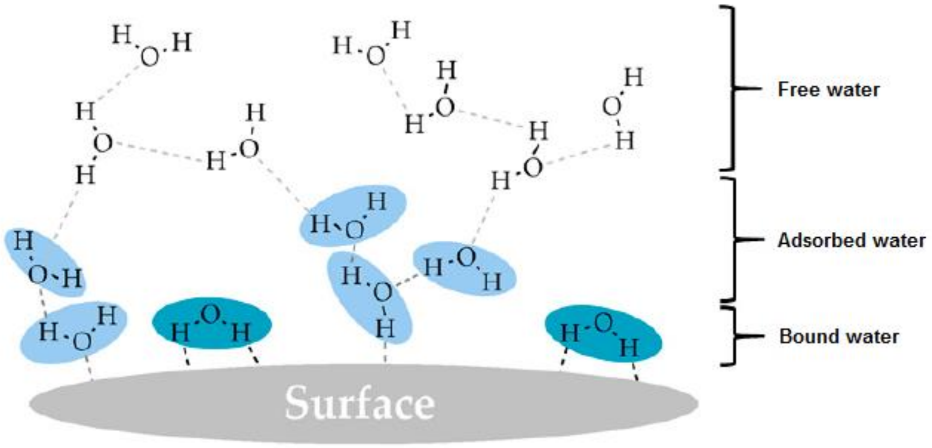

Figure 2.1 -Types of water present in the food materials [8]

Free Water:

The water which can be squeezed out of the food is called the free water and, it is the most dominant form of water presence in the food. Free water can be easily removed from food by drying compared to other forms of water.

Adsorbed water:

The water, which is attached by the hydrogen bonds to the food cellulose molecular or ionic sites on molecules called adsorbed water. Adsorbed water can be released when cutting or damaging the food. therefore, adsorbed water can release and act as free water in different situations. Hence, adsorbed water can contribute to the growth of microorganisms. Hence, during food drying, adsorbed water must be removed from the food material to preserve the foods.

Bound water:

The water which is strongly bonded to the atomic structure of the food is called as the bound water. Due to its strong bond, that is not acting as a solvent. Therefore, bound water is not free to act as a solvent for salt or sugar. Bound water molecules cannot escape as a vapor because of their strong bond with food molecules. So, bound water does not produce the vapor pressure and it does not contribute to any microorganism activity. Thus, bound water is not necessary to be removed in food drying even though it cannot be removed by hot air drying.

2.2 The measure of moisture contained in a food material

The moisture contained in a food material is measured in two bases.

i. Wet basis
ii. Dry basis

The wet basis MC is the ratio between the weight of the water contained in the food and the total weight of the food, and it can be calculated using Equation 2.1 [9].

$$MC(wb)_t = \frac{W_t - W_d}{W_t} \times 100 \qquad 2.1$$

Where,

$MC(wb)_t$	:	Dry basis MC at time t in drying,
W_t	:	Sample weight at time **t** in drying,
W_d	:	Dry matter weight in the sample.

The dry basis MC is defined the ratio between the weight of the water contained in the food and the weight of the dry matter in the food, and it can be calculated using Equation 2.2 [9].

$$MC(db)_t = \frac{W_t - W_d}{W_d} \times 100 \qquad 2.2$$

Where,

$MC(db)_t$	:	MC in dry basis at time t in drying,
W_d	:	Weight of the dry matter in the sample.

2.2.1 Relationship in between dry basis MC and wet basis MC

The following relationship can be established between the dry basis MC and the wet basis MC

.

$$Moisture\ content\ (wet\ basis) = \frac{weight\ of\ the\ water\ in\ food}{total\ weight\ of\ the\ food} \qquad 2.3$$

Total weight of the food can be written as the sum of the weight of the water in the food and dry matter in the food.

$$MC\ (wet\ basis) = \frac{weight\ of\ the\ water\ in\ food}{weight\ of\ the\ water\ in\ food + weight\ of\ the\ dry\ matter\ in\ the\ food} \qquad 2.4$$

$$MC\ (wet\ basis) = \frac{\left(\frac{W_t - W_d}{W_d}\right)}{\left(\frac{W_t - W_d}{W_d} + \frac{W_d}{W_d}\right)} \qquad 2.5$$

$$MC\ (wet\ basis) = \frac{MC\ (dry\ basis)}{MC\ (dry\ basis) + 1} \qquad 2.6$$

Similarly, $$MC\ (wet\ basis) = \frac{MC\ (wet\ basis)}{1 - MC\ (wet\ basis)} \qquad 2.7$$

2.2.2 Equilibrium MC

The movement of moisture from food to air or vice versa is determined by the gradient of water vapor pressure. The equilibrium condition is defined as the situation in which the vapor pressure produced by the moisture of the food materials equals to the vapor pressure of the surrounding atmosphere, with no net movement of moisture in either direction. The moisture level of food in equilibrium is referred to as the food's equilibrium MC.

The equilibrium MC of a food material can be calculated using the Equation 2.8. [9].

$$M_{eg} = E - F\,ln[-(t + C)lnRH] \qquad 2.8$$

Where,

M_{eg}	:	Equilibrium MC (dry basis)
E, F, C	:	Food material dependent constant
T	:	Temperature in Celsius
RH	:	Relative humidity of air in decimal

The variation of the MC with the RH of air in drying is given by adsorption isothermal curves. Typical adsorption isothermal curves for some food materials are given in Figure 2.4

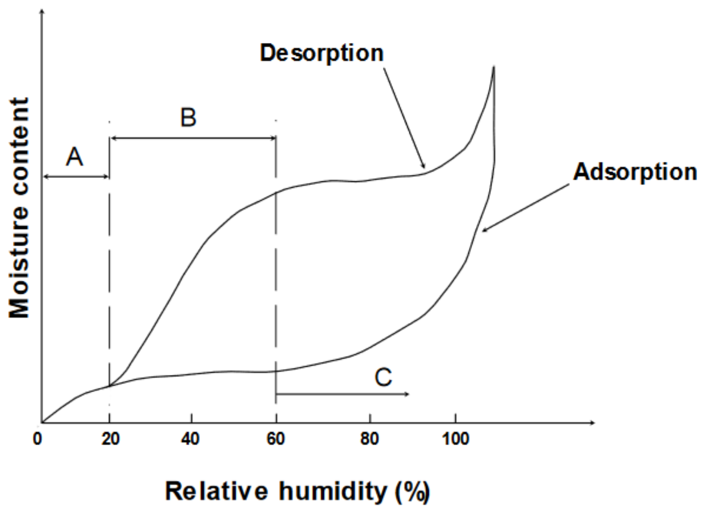

Figure 2.4 - Typical adsorption isothermal curve for a food material [12]

2.2.3 Moisture Ratio

The MR for a food material is defined by the Equation 2.6 [9].

$$MR_t = \frac{MC(db)_{t=t} - M_e}{MC(db)_{t=0} - M_e} \qquad 2.6$$

Where,

MR_t	:	MR at time t in drying,
$MC(db)_{t=t}$	:	Dry basis MC at time t in drying,
$MC(db)_{t=0}$	:	Initial MC in (dry basis),
M_e	:	MC at equilibrium condition.

The equilibrium MC M_e is very small compared to $MC(db)_{t=t}$ and $MC(db)_{t=0}$. Hence above equation can be simplified as Equation 2.7 [11].

$$MR_t = \frac{MC(db)_{t=t}}{MC(db)_{t=0}} \tag{2.7}$$

2.3 Water activity of a food material

Bound water in the food cannot be used by the microorganisms. However, they can use some portion of adsorbed water to the growth. Therefore, absolute MC is not the most suitable measure to predict the rate of growth of microorganisms. As a result, the term "water activity" was introduced to describe the amount of water accessible for microbial development. The fraction in between the partial vapor pressure of water in food to the partial vapor pressure of pure water at the same temperature is called water activity, and it ranges from 0 to 1.

$$Water\ activity = \frac{partial\ vapor\ pressure\ of\ water\ in\ a\ food}{partial\ vapor\ pressure\ of\ pure\ water} \tag{2.8}$$

The rate of growth of microorganisms increases with the water activity of the food. For most of the food materials the growth of mold, yeast and bacteria begins at the water activity of 0.6, 0.8 and 0.9 respectively as shown in Figure 2.5.

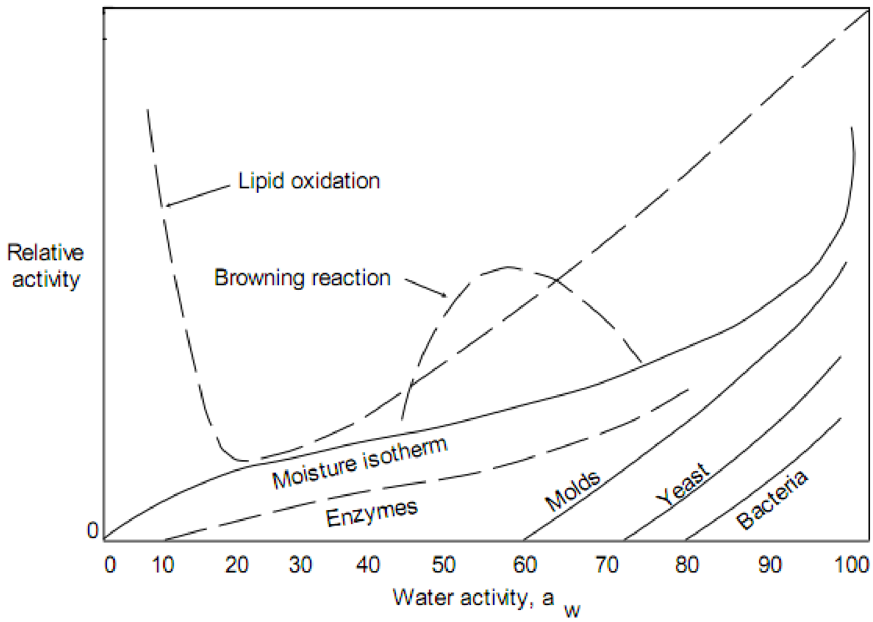

Figure 2.5 - The relative activity of microrganisms with the water activity [12]

Growth of molds starts at the water activity closely at 0.6

Figure 2.6 - The mould micro organism [pixabay image gallery]

Growth of yeast starts at the water activity level of 0.8

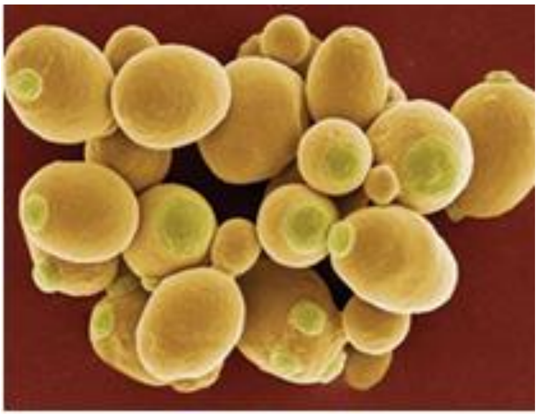

Figure 2.7 - The yeast microorganism [pixabay image gallery]

Growth of bacteria starts at the water activity level of 0.9

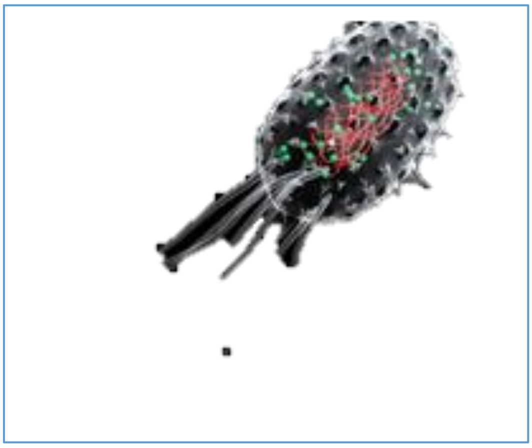

Figure 2.8 - The bacteria microorganism [pixabay image gallery]

2.4 Hot air-drying Mechanism

The process of removing moisture from food is known as food drying. It's a multi-step transient process involving both heat and mass transmission. In the food sector, convective heated air drying is the most prevalent drying technique. In hot air drying, the liquid water contains in the food is converted to vapor phase and transport away from the food. The following three processes occur simultaneously in convective hot air drying.

1. Transfer of heat from hot air to the food.
2. Internal moisture is transferred to the food's surface.
3. Transport of evaporated moisture with the hot air.

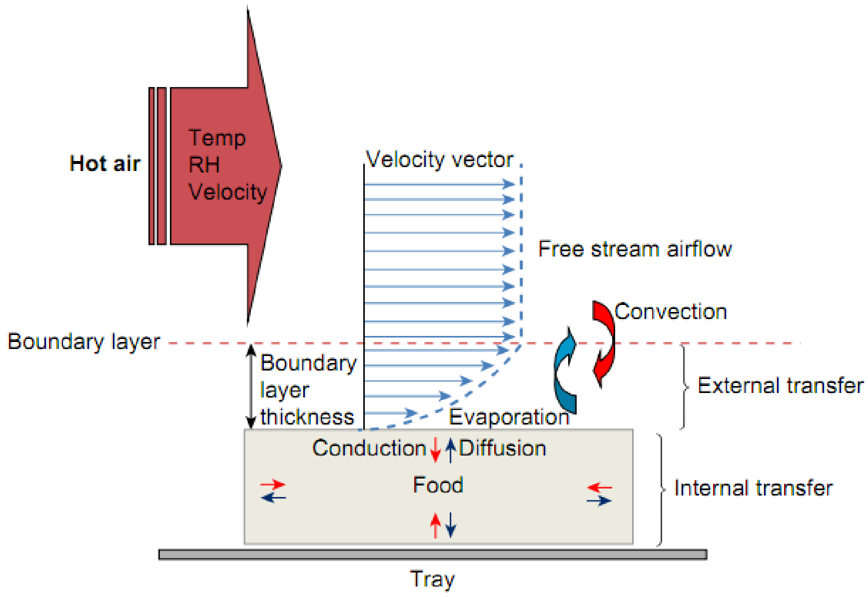

Figure 2.9 - A conceptual illustration of a solid food material drying by hot air [13].

The rate at which the above three processes occur determines the rate of drying. Details of these three processes are given below

2.4.1 Transfer of heat from heated air to the food material

The rate of heat transfer between heated air and food stuff is determined by, the temperature of heated air and food material, amount of turbulence of the air flow, and surface property like hardness and porosity of the food stuff. As illustrated in Figure 2.12, the total drying time can be divided into 4 sections as the initial period, steady rate period, first dropping rate period, and the second dropping rate period. During the initial period, the food material is heated up from room temperature, so that heat transfer rate is very high. The amount of heat transfer falls with the increase of food temperature. The amount of heat transfer is constant during the constant rate period. because the supplied energy spends to evaporate the surface water whereas the temperature of the food material remains constant. First dropping rate period begins after evaporation of all the surface water. In this period, internal water must travel to the food surface for evaporation, which needs a higher temperature gradient, so that the food surface temperature increases. Consequently, the rate of heat transfer gradually reduces.

Internal moisture migration to the food surface is mainly dependent on the food matrix properties. Moisture migration inside the solid can be caused by one or more of the following methods.

1. **Liquid diffusion:** In hot air drying the surface of the food material directly expose to the hot air, which results in lowering of the surface MC and subsequently develop a moisture concentration differential between the food's interior and exterior surfaces. This concentration gradient produces the motive force to migrate the internal water to the surface.

2. **Capillary movement:** Capillary flow transports unbound liquid water to the food's outer surface via the porous paths.

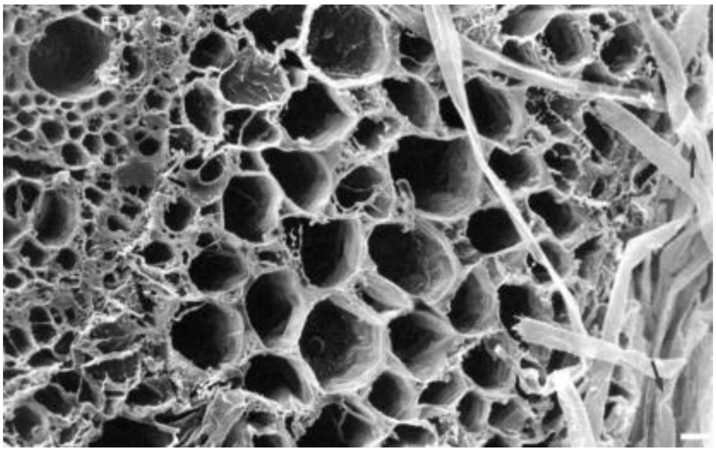

Figure 2.10 - porous capillaries in food material [14]

In the static condition liquid water rises through a narrow porous to a height of h according to the Equation 2.9 [14] as shown in the Figure 2.11.

$$h = \frac{2\gamma}{\rho g r} \cos\theta \qquad 2.9$$

Where,

γ	:	Surface tension of the water,
θ	:	Contact angle,
ρ	:	Density,
g	:	Gravitational constant,
r	:	Radius of the capillary tube.

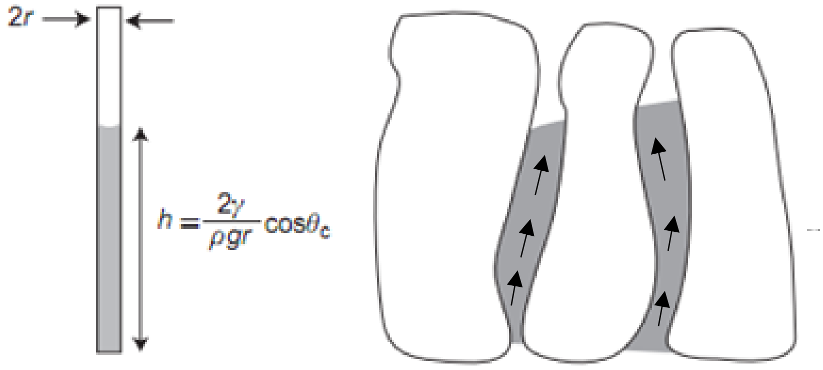

Figure 2.11 - Capillary flow of water through food porous [14]

3. **Vapor diffusion:** During the drying, internal moisture may evaporate and diffuses outward of the food material as the vapor.
4. **Pressure:** Shrinkage of the outer layer of the food material in drying causes to develop the pressure inside it. Consequently, the internal water moves to the food's exterior surface.

2.4.3 Transfer of evaporated moisture with the hot air

Transferring evaporated vapor away from the food material is important to produce a less humid environment near the food material, which is being dried. It increases the moisture diffusivity and, as well as the drying rate. This method of mass transfer mainly depends on the heated air velocity. Moreover, the moisture-transfer rate and the moisture diffusivity rate increase with the air velocity. Therefore, there is an optimum drying air velocity which maximize the moisture transfer while minimizing the total drying energy.

2.5 Drying Rate Curves

The rate of drying in relation to the MC of a food material is represented by the drying rate curve as depicted in Figure 2.12. This curve is obtained under the uniform drying conditions and is unique for the food material. The vapor pressure gradient established at the boundary layer determines the rate of evaporation of water from food material in the convective heated air-drying process. If the vapor pressure gradient is zero, there is no net moisture movement in either direction. and this condition is called as the equilibrium condition. The moisture level at the equilibrium condition is called as the equilibrium MC. The MC that is greater than the equilibrium MC is referred to as free moisture (X) and it can be evaporated and removed by supplying hot air. Equation 2.10 [1] can be used to determine the free MC.

$$X = X_t - X^* \tag{2.10}$$

Where,

X	:	Free MC in dry basis,
X_t	:	Dry basis MC of the food material,
X^*	:	Dry basis equilibrium MC for a given humidity and temperature.

The Rate of Drying is defined by the following equation.

$$R = -\frac{M_s}{A}\frac{dX}{dt} \tag{2.11}$$

Where,

R	:	Rate of drying in kg of water/h.m^2,
M_s	:	Dry solid in food material in kg,
A	:	food surface is exposed to the drying in m^2,
$-\frac{dX}{dt}$	:	Rate of loss of free moisture.

2.5.1 The typical variation of rate of drying against the drying time for a food material

The drying rate for the steady state drying condition highly depends on the kind of food that needs to be dried and it is unique for the food material. The typical Variation in drying rate with the drying time for a food material is given in Figure 2.12.

Line A to B: Drying process starts at A. During this period, the supplied thermal energy uses to increase the temperature of loaded material from ambient temperature to the equilibrium temperature.

Line B to C: Initially the food surface is enclosed by a thin layer of free water. This free water begins to evaporate in this period. In this period rate of drying and temperature remains constant and all the transferred heat is contributed to evaporate the surface water.

Line C to D: The drying rate falls with the absence of surface water. The critical MC is referring to the MC at the beginning of this fall rate period. During this period, water must transfer from inner body to the outer surface for evaporation. The rate of drying in this period is mainly governs by the rate of moisture transfer to the food surface from the internal. The rate of drying, R, highly depends on the food matrix properties.

Line D to E: Only some adsorbed water remains in the food material after the first dropping rate period and water remains are strongly bonded to the food matrix. Hence, these water molecules cannot be easily removed and the rate of drying further drops exponentially in this period.

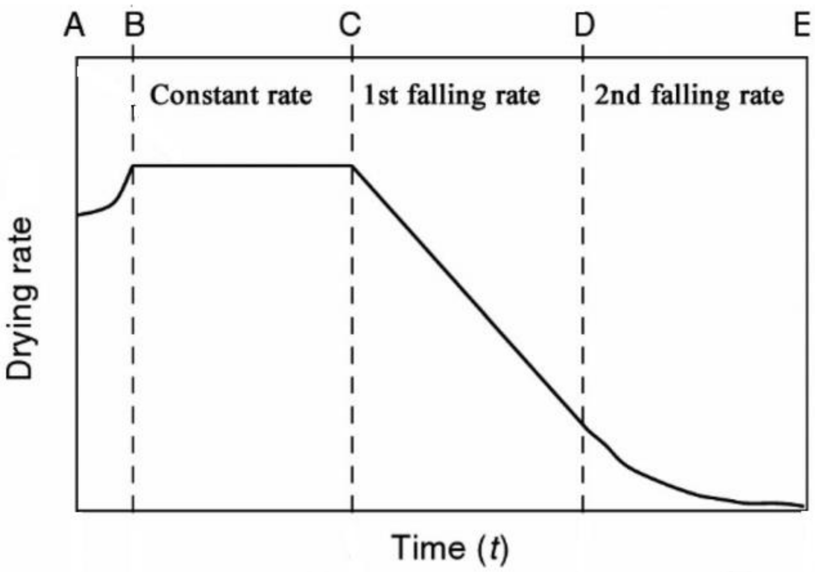

Figure 2.12 - Typical hot air drying rate curve under Constant drying conditions [15]

2.5.2 The typical variation of MR against the drying time

The variation of MR of a food material against the time under steady state drying conditions is unique for the food material being dried. Therefore, a typical food drying curve is given in Figure 2.13.

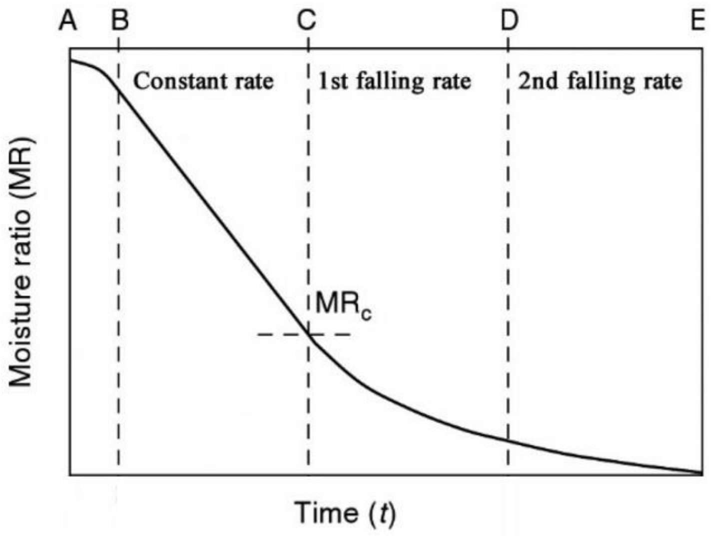

Figure 2.13 - Variation of MC with the drying time [15]

2.5.3 The typical food temperature variation with the drying time

During A-B period, the supplied thermal energy is used to increase the temperature of loaded material from room temperature to the equilibrium temperature. During the constant temperature period (B-C), all the supplied energy is consumed to evaporate the free water presence at the outer surface. So that the temperature remains constant. After evaporation of all the surface water first dropping rate period begins. During this period food temperature increases and the internal moisture migrates to the food surface for evaporation. During the second dropping rate period (D-E), the temperature further increases because of the decreased rate of evaporation.

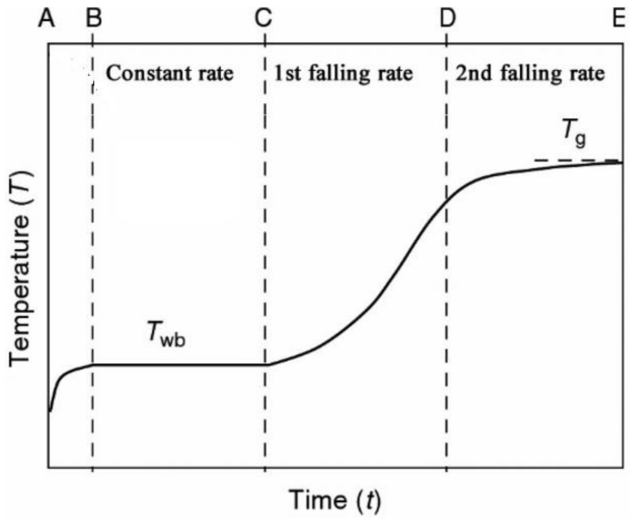

Figure 2.14 - Variation of food temperature with the drying time [15]

2.6 Thin layer drying

Drying a food material by exposing it to a thin layer of hot air is called the thin layer drying. Most of the DMs are evolved considering the thin layer drying process.

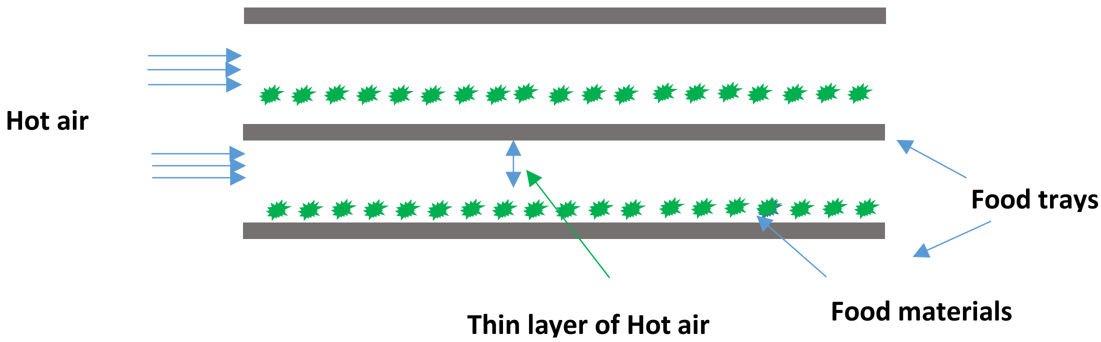

Figure 2.15 - Thin layer drying process

2.6.1 Thin layer DMs

The drying kinetics of porous substance such as food, paper, and fabric are described using thin-layer DMs. Theoretical, semi-theoretical, and empirical DMs are the three types of thin layer DMs based on their derivation. However, the most applicable DM categories are semi theoretical, and empirical models because these DMs are developed based on experiments, so that it includes all the physical parameters which are not normally included in the theoretical models.

2.6.1.1 Theoretical DMs

The theoretical DMs are developed considering the interior moisture transfer resistance within the food material and, moisture transfer resistance to the outside air. The majority of theoretical DMs are developed using the Fick's Second Law of Diffusion [16].

2.6.1.2 Semi-theoretical DMs

Semi-theoretical DMs are obtained by combining theoretical DMs or simplifying them. The following are the most commonly utilized semi theoretical DMs in the literature.

Newton (Lewis) Model

This model has been developed using Newton's cooling law. It is the simplest model describes the variation in MR as a function of drying time. Because it has only one constant as shown in the Equation 2.12 [15].

$$MR = \exp\ (-kt) \qquad 2.12$$

Where,

MR	:	Dimensionless MR at time t,
k	:	Drying constant (s^{-1}),
t	:	Drying time t.

Page Model

Page model has been developed by modifying the Newton Model. As a result, the Newton Model's errors have been significantly reduced. The variation of MR with the time in the Page DM is given by Equation 2.13 [15].

$$MR = \exp\ (-kt^{n}) \qquad 2.13$$

Where,

MR	:	Dimensionless MR at time t,
k	:	Drying constant (s^{-1}),
t	:	Drying time t,
n	:	model constant (dimensionless).

Henderson and Pabis DM

This DM was developed by simplifying the general solution of Fick's partial differential equation for diffusion. This model is also a simple model and has only two constants [18]. The variation of MR with the drying time in the Henderson and Pabis Model is given by Equation 2.14 [15].

$$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt}) \qquad 2.14$$

Where,

MR	:	Dimensionless MR at time t,
k	:	Drying constant (s^{-1}),
t	:	Drying time t,
a	:	Dimensionless constants depend on shape of the food.

Two Term DM

This DM was developed using the second term of Fick's Second Law of diffusion's general solution. This model contains two empirical constants which should be determined experimentally. The first term of the model explains the end of the drying process, whereas the second term explains the initiation of the drying process. Two term DM is most suitable to explain the drying kinetics of the vegetables and fruits. The variation of MR with the time in the Two-Term DM is given by Equation 2.15 [15].

$$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{k_0 t}) + \mathrm{b}\exp(-\mathrm{k_1 t}) \qquad 2.15$$

Where,

MR	:	Dimensionless MR at time t,
k_0, k_1	:	Drying constants (s^{-1}),
t	:	Drying time t,
a,b	:	Model constants.

Midilli Model

Midilli Model has been developed by adding the extra empirical term to the Pabis Model. It consists of exponential term and a linear term. The variation of MR with the drying time in the Midilli Model is given by Equation 2.16 [15].

$$MR = a \exp(-kt^n) + bt \qquad 2.16$$

Where,

MR	:	Dimensionless MR at time t,
k	:	Drying constant (s^{-1}),
t	:	Drying time t,
a	:	Dimensionless constants depend on shape of the food,
n	:	Dimension less model constant,
b	:	Empirical constant (s^{-1}).

Logarithmic DM

Chandra and Singh proposed the Logarithmic Model in 1995. This model has developed by adding an empirical constant to the Henderson and Pabis Model. The Equation 2.17 [15] gives the variation of MR with the drying time in the Logarithmic Model.

$$MR = a \exp(-kt) + b \qquad 2.17$$

Where,

MR	:	Dimensionless MR at time t,
k	:	Drying constant (s^{-1}),
t	:	Drying time t,
a	:	Dimensionless constants depend on shape of the food,
b	:	Dimension less empirical constant.

2.6.1.3 Empirical models

Empirical DMs are derived using the experimental data. The MR and drying time have a direct relationship according to an empirical model. The most common empirical DMs are the Wang and Singh, Weibull and Diamante.

Weibull Model

In the literature, the Weibull Model is the most commonly used empirical model. This DM was developed based on practical data. The Equation 2.18 [15] gives the variation of MR with the drying time in the Weibull Model.

$$MR = a - b \, exp\,(-kt^n) \qquad 2.18$$

Where,

MR	:	Dimensionless MR at time t,
t	:	Drying time t,
a, b, k, n	:	Empirical constants.

Wang and Singh DM

Wang and Singh developed this model in 1978 based on data obtained from rice drying experiments. This model does not include any theoretical interpretation.

$$MR = 1 + at + bt^2 \qquad 2.19$$

Where,

MR	:	Dimensionless MR at time t,
t	:	Drying time t,
a, b	:	Empirical model constants.

Diamante Model

This DM was developed to represent the drying kinetics of kiwi and apricot fruits. This model was constructed using the experimental data. The Equation 2.20 [15] gives the variation of MR with the drying time in the Diamante Model.

$$\ln\,(-\ln MR) = a + b\,(\ln t\,) + c\,(\ln t\,)^2 \qquad 2.20$$

Where,

MR	:	MR at time t,

t	:	Drying time t,
a, b, c	:	Empirical model constants.

2.6.3 Thin layer drying experimental setup to determine the drying rate curve

Because the drying rate curve is unique to the food item, it must be determined using experimental approaches. Figure 2.16 shows an experimental setup for determining the rate of drying for food materials. The food which is to be tested should be placed on the tray which is suspended on a balance and exposed to hot air. The drying rate is calculated by weighing the sample at regular intervals.

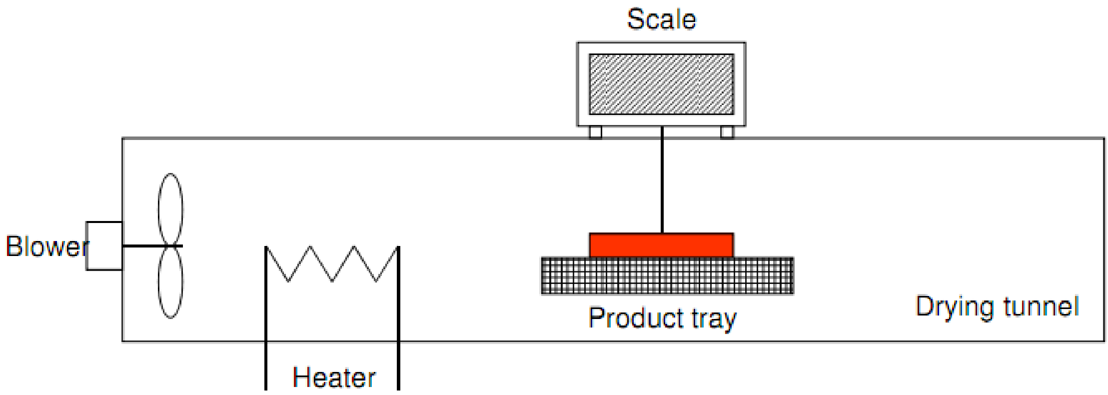

Figure 2.16 – Apparatus to determine the drying rate curve

2.7 Calculation of effective moisture diffusivity (Deff)

Diffusion of moisture inside the food material is a complex process which involves several sub-processes. The effectiveness of all of these sub-processes to the moisture transport is represented by only one parameter called effective moisture diffusivity. Effective moisture diffusivity is a function of the drying temperature and MC of certain food materials. The effective moisture diffusivity is the governing constant that describes the moisture transport mechanism in drying. In most of the cases, effective moisture diffusivity is calculated using the experimental drying curves interpreted with Fick's law of iffusion as shown in Equation 2.21 [17].

$$\frac{\partial MR}{\partial t} = \nabla[D_{eff}\nabla(MR)] \qquad 2.21$$

Where,

MR	:	MR at time t,
t	:	Drying time t,
D_{eff}	:	Effective moisture diffusivity.

The solution for the Equation 2.21 for various geometries has developed by Crank in 1975. The solution for spherical geometry is presented in Equation 2.22 [18].

$$\mathrm{MR} = \frac{6}{\pi^2}\sum_{n=1}^{\alpha}\frac{1}{n^2}\exp\left[\frac{-n^2\pi^2}{R}\left(\frac{D_{eff}\,t}{R}\right)\right] \qquad 2.22$$

Where,

MR	:	Dimensionless MR at time t,
t	:	Drying time t (s),
D_{eff}	:	Effective moisture diffusivity (m^2/s),
n	:	Number of terms,
R	:	Particle radius (m).

The Equation 2.22 can be further simplified by taking only the first term and neglecting the other terms of the summation (Why??) and it is represented in Equation 2.23 [18].

$$\ln(\mathrm{MR}) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2\,D_{eff}}{R^2}\right)t \qquad 2.23$$

Where,

MR	:	Dimensionless MR at time t,
t	:	Drying time t (s),
D_{eff}	:	Effective moisture diffusivity(m^2/s),
R	:	Particle radius (m).

The plot of logarithmic value of the MR against the time is a straight line with a gradient of $-\left(\frac{\pi^2\,D_{eff}}{R^2}\right)$, that can be used to find the effective diffusivity as given in Equation 2.24 [17].

$$D_{eff} = \left(-\frac{4R^2}{\pi^2}\right) \times Gradient \qquad 2.24$$

2.7.1 Activation Energy Calculation (E_a)

The effective moisture diffusivity mainly depends on the drying air temperature and amount of MC of the food material. This effect can be represented by using the Arrhenius Equation as given by Equation 2.25 [17].

$$D_{eff} = D_0 exp\left(-\frac{E_a}{RT}\right) \qquad 2.25$$

Where,

D_{eff}	:	Effective moisture diffusivity(m^2/s),
D_0	:	Pre exponential factor (m2/s),
E_a	:	Activation energy (J/mol),
R	:	Universal gas constant (J mol-1 K-1),
T	:	Absolute temperature (K).

The activation energy is a very important variable that governs the drying process and describes the required energy level for water molecules to evaporate through diffusion. The activation energy mainly depends on the drying temperature. The activation energy can be calculated by rearranging the Equation 2.25, as shown in the Equation 2.26.

$$\ln(D_{eff}) = -\left(\frac{E_a}{R}\right)\left(\frac{1}{T}\right) + \ln(D_0) \qquad 2.26$$

The plot of ln (D_{eff}) against the 1/T has a linear relationship with a gradient of $-\left(\frac{E_a}{R}\right)$, which can be used to find the activation energy as given in Equation 2.27 [17].

$$E_a = -R \times (\text{gradient of the plot}) \qquad 2.27$$

2.8 Calculation of total drying time

The total time taken to reduce the food MC to the recommended safe storage MC is called the total drying time. It can be calculated using the MR curve as follows,

Let the safe storage MC limit = $MC(db)_{t=T}$

MR value at this limit =MR_T

$$MR_T = \frac{MC(db)_{t=T}}{MC(db)_{t=0}} \qquad 2.28$$

The total drying time T can be calculated by substituting the MR_T in the matching DM equation.

2.9 Energy utilization in convective heated air drying

2.9.1 Total drying energy

The total energy for convective heated air drying is the sum of thermal energy to produce heat and the mechanical energy to drive fans, and it is estimated by Equation 2.29 [17].

$$E_{Total} = E_{thermal} + E_{mechanical} \qquad 2.29$$

Where,

E_{Total}	:	Total drying energy,
$E_{thermal}$	:	Total thermal energy,
$E_{mechanical}$	:	Total mechanical energy.

2.9.2 Energy consumption breakdown in convective hot air-drying process

Approximately 85% of industrial dryers are categorized as convective type hot air dryers [9]. The average specific heat consumption measured from practical hot-air food dryers may vary between 4–8 MJ/kg^{-} [2]. In addition to thermal energy, hot air dryers consume electricity as well to produce the momentum for hot air. However, the electric energy consumption is negligible (which is about 5-8%) with comparative to thermal energy [7].

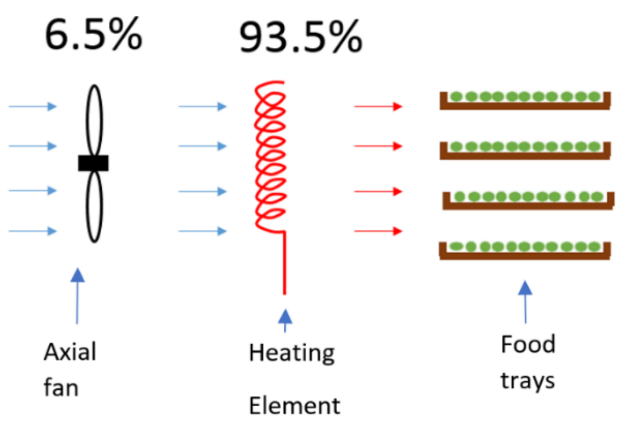

Figure 2.17 - Percentage wise energy utilization in convective hot air drying

2.9.2 Total thermal energy in hot air drying

Thermal energy needed for the drying process can be determined by the Equation 2.30[17].

$$\boldsymbol{E_{thermal}} = \mathrm{A.V.\rho.C.(t - t_{amb}).T} \qquad 2.30$$

Where,

V	:	Air flow velocity through the food trays,
t	:	Drying air temperature,
t_{amb}	:	Ambient temperature,
ρ	:	Density of air,
C	:	Specific heat capacity of the air,
T	:	Total drying time,
A	:	Total air gap between the trays.

2.9.3 Energy consumption by the sub-processes during the drying process

energy consumption by sub-processes during the drying process was examined by a research group of Helsinki University and is shown in Figure 2.18. Approximately half of the heat is consumed for evaporation of water, while a significant amount of heat is lost as the sensible heat in the exhaust air. moreover, there is a considerable heat loss via conduction and radiation from the dryer at the outer surfaces and rest is consumed for heating the grains of the food material.

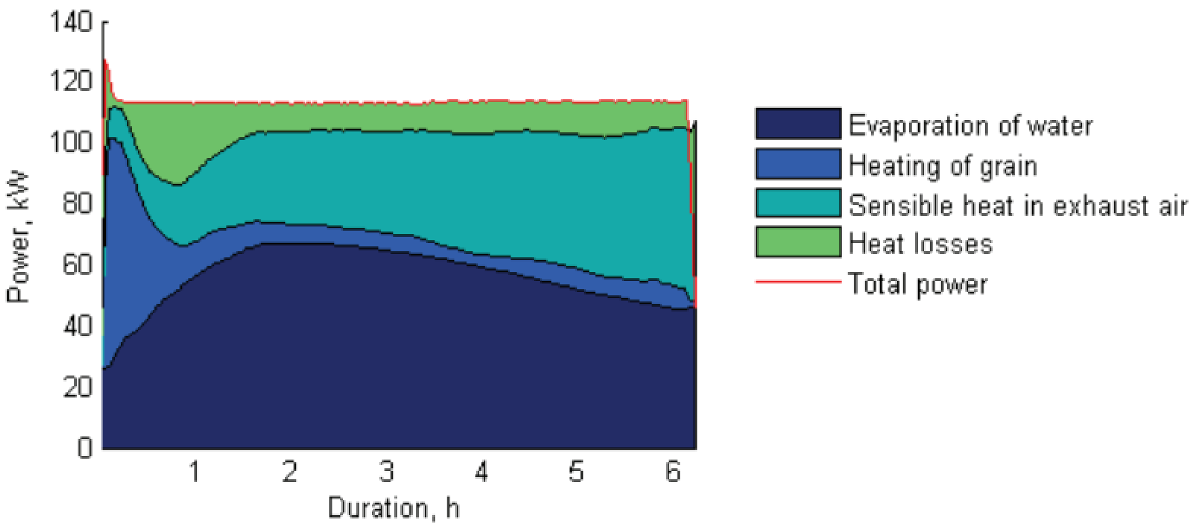

Figure 2.18 - Allocation of energy in food drying process [19].

2.10 Food Dryers

2.10.1 Classification of dryers

In the food drying sector, there are several different types of dryers and hence the precise classification of these dryers is very difficult. However, they May be classified into categories as stated in the Table 2.1.

Table 2.1 - General classification of food dryers

Classification	Types of dryers (General characteristics and applications)
Type of feed material	• Particle • Slurry/paste /sludge • Liquid suspension
Processing mode	• Batch • Continuous
Mode of heat transfer	• Convection • Conduction • Electromagnetic (Microwave, infrared, osmotic) • Combination
Energy source	• Solar • Electricity • Biomass • Fossil Fuel
Product temperature	• Above freezing point • Below freezing point
Operating pressure	• Atmospheric • Vacuum • High pressure

Cabinet type tray dryers

Cabinet type tray dryers are operated in batch mode. The trays of the dryer are used to hold the products. These dryers are convective-type hot air dryers which utilize hot air as the drying medium. Hot air carries heat to the food material and its momentum removes the evaporated moisture from the food surface. These dryers are extremely popular in the small-scale food industry. Drying time may vary between 2-12 hrs mainly depending on the type of food being dried and hot air temperature and velocity.

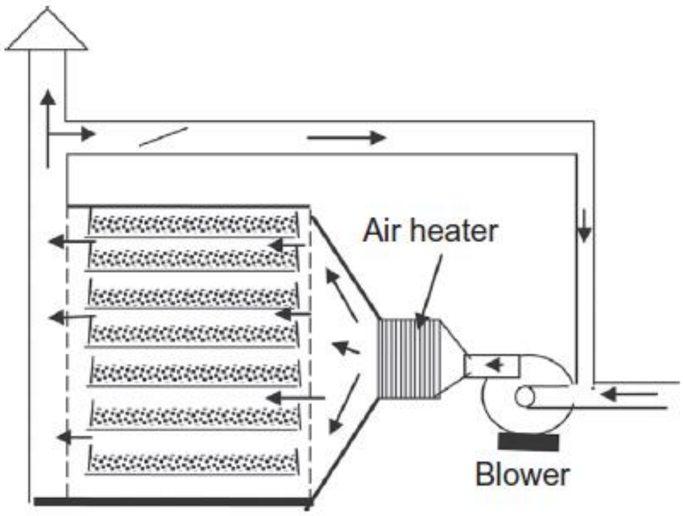

Figure 2.19 - Cabinet type tray dryer [20]

Belt dryers

Belt dryers are continues-type of hot air dryers and are commonly use in the large-scale food processing industry due to their huge capacity. Belt dryers are of two types and are single state belt dryers (consist only one belt) and, multi-state belt dryers (consist of several belts arranging in different levels as shown in Figure 2.20). Multistate dryers can be used to obtain uniform drying characteristics, as the drying material mixes properly when it passes through the multiple number of belts.

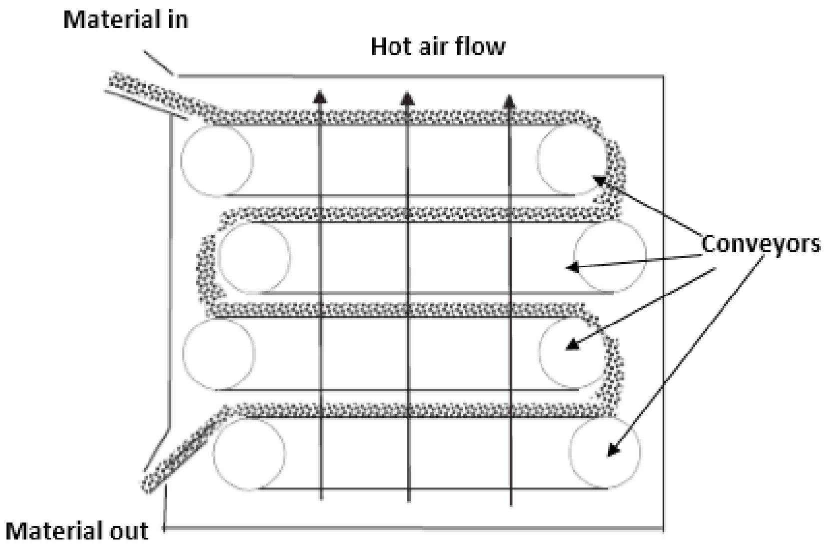

Figure 2.20 - Cabinet type tray dryer [20]

Rotary dryers

In the chemical and mining industries, rotary dryers are commonly utilized. The dryer consists of a steel cylinder with internal louvers. During the operation, the cylinder rotates in an inclined position, and material is fed at a higher elevation end and discharge at the bottom end. Hot air blows from the bottom and escapes from the top to have a cross flow heat exchange.

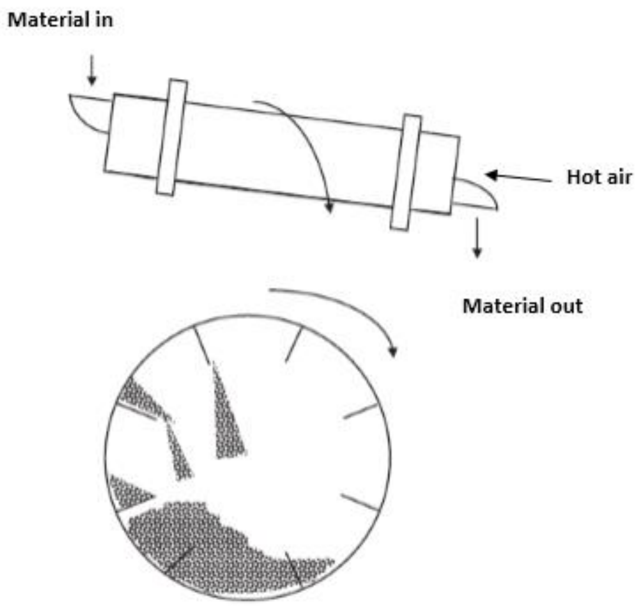

Figure 2.21- Rotary dryer [20]

Solar dryers

Solar dryers operate by utilizing the solar heat. There are two kinds of solar dryers direct dryers and indirect dryers. Direct solar dryers food materials are directly exposed to the direct sunlight while in indirect solar dryers food materials are not directly exposed to the sunlight. In indirect solar dryers, a solar heat collector heats the incoming air, which is then forced to pass through the food trays by a draft fan.

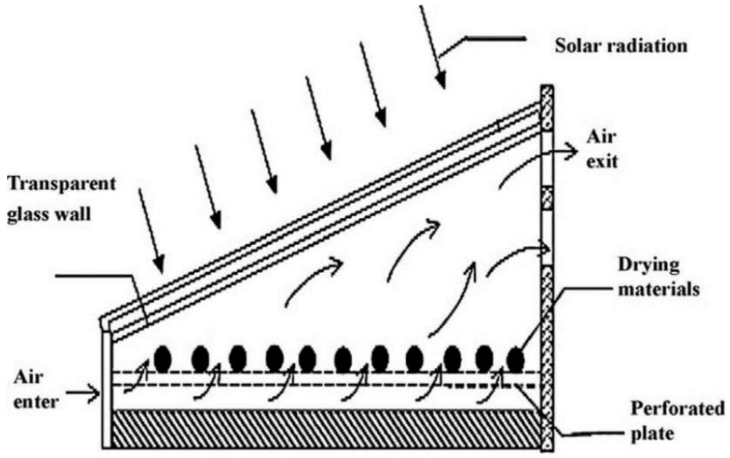

Figure 2.22 - direct solar dryer [20]

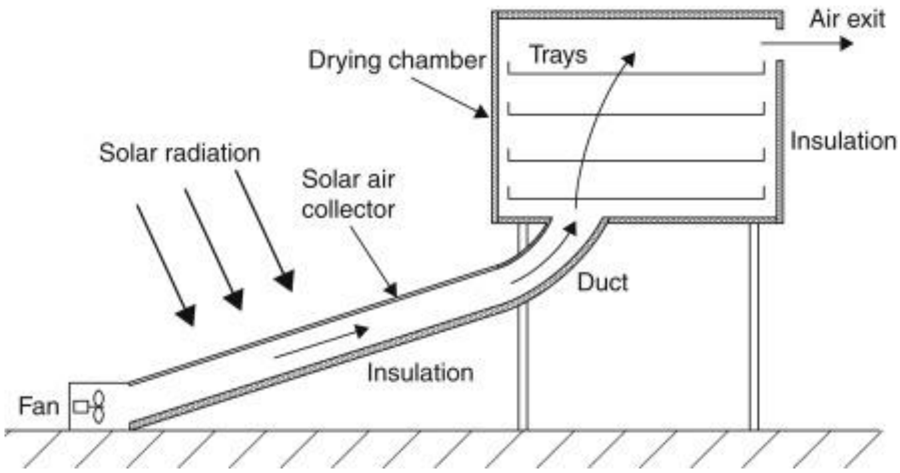

Figure 2.23 - Indirect solar dryer [20]

Fluidized bed dryers

Hot air is forced through the food cabin at a high enough velocity to fluidize the food materials in fluidized bed dryers. Uniform and efficient drying can be obtained due to the efficient mixing process takes place in the dryer. There are two types of fluidized bed dryers and are batch type and continuous type.

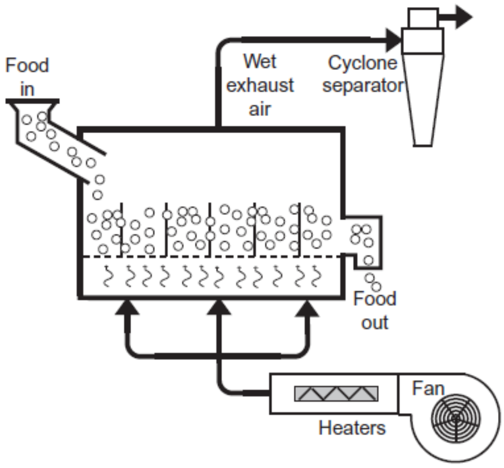

Figure 2.24 - Fluidized bed dryers [14]

Spray dryers

Spray drying is a method to convert liquid food to a dry powder by rapidly drying using hot air. This method is applied for the preparation of foods such that milk powder, coffee, spices, flavors, vitamins, enzymes, and colorings. A spray dryer consists of a feed pump, spray nozzle, hot air generator, drying chamber and a cyclone separator. In the typical operation, the atomizer sprays liquid food at the top of the drying chamber while hot air passes upstream through the drying chamber. Liquid droplets reaching to the bottom get dried and converted to powder form. The cyclone separator is used to separate the dried powder.

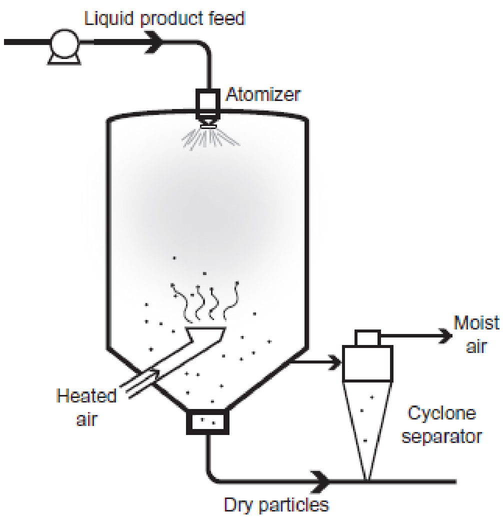

Figure 2.25 - Spray dryer[14]

2.11 Effect of drying on food quality

Food quality changes during any food drying process as it could lead to loss of nutritious values, loss of volatile oil, and change in texture, flavor, color, and smell. Some of these factors can be minimized by selecting the suitable food drying technique and process parameters. Among the various issues in the food drying process, two of them were identified as significant and are:

1. Drying non-uniformity
2. Loss of volatile substances

2.11.1 Drying non-uniformity

Food material being dried could reach at different moisture levels after a certain period of drying is called drying non-uniformity. In some food drying processes, food materials on all the surfaces are not exposed to similar drying conditions and, as a result, this drying non-uniformity occurs. Geometric non uniformity of the food also causes the drying non-uniformity. Drying non-uniformity is common with dryers, which are not having a proper mixing mechanism during the drying operation. Most of the batch dryers encounter drying non-uniformity. Food material that is closer to the hot air inlet reaches the maximum drying conditions and dry faster than in the other areas. Over drying may lead to loss of volatile substances while under drying of the products may lead to perish in storage. Thus, non-uniformity in drying produces lower product quality and higher energy consumption. Non-uniformity drying is one of the major problems encountered with the cabinet-type tray dryers. This can be minimized by introducing a uniform air flow distribution and by maintaining uniform turbulence.

2.11.2 Loss of volatile substances

Essential oil is a liquid, which contains volatile compounds extracted from plants. Some food materials such as spices and herbal plants, contain a higher amount of essential oils. Essential oils provide a unique flavor and smell to the food materials and some of them have strong health benefits. Therefore, selection of drying method and drying parameters are very important to reduce the loss of essential oil from the food material. Essential oils are highly sensitive to temperature hence controlling drying temperature is an important factor to prevent essential oil loss in drying. Drying in low temperatures is the most preferred method to reduce the evaporation of essential oils. But drying at a very low temperature causes higher exposure time to hot air and hence it results to increase the loss of essential oils.

CHAPTER 3

3. RESEARCH METHODOLOGY

3.1 Selection and preparation of raw black pepper for the experiment

Black pepper variety, Paniyur-1 was selected for this experimental study as it is the most commonly available black pepper variety cultivates in Sri Lanka. Well matured freshly harvested black pepper was used for this experiment.

3.2 Experimental Set

An experimental apparatus of a convective tray dryer was designed and manufactured to monitor the drying behavior of black pepper. The schematic diagram of the component layout and the locations of the measuring devices of the test rig are labeled and illustrated in Figure 3.1.

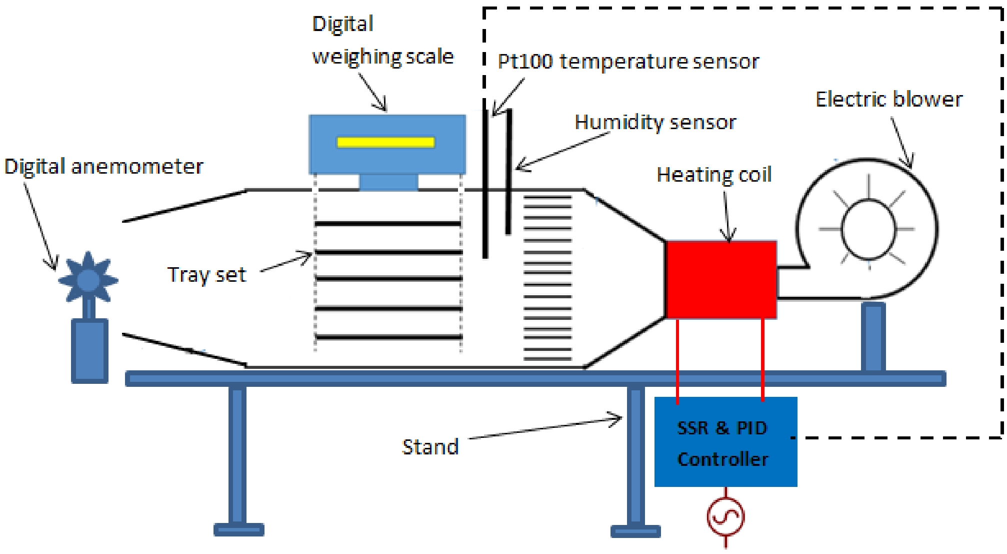

Figure 3.1 - Schematic diagram of the experimental set-up

As shown in the above figure, it consists of an air blower, electric heating coil, flow strainers, five food trays, digital weighing scale, thermometer, and an airflow meter. The fabricated test rig is shown in Figure 3.2. The power rating of the blower is 450 W and, it is equipped with a flow control device. The heater has a capacity of 3 kW, and it was controlled using a solid-state relay (SSR) according to the signal provided by the PID temperature controller (CXR100). Flow strainers were used to ensure a uniform laminar airflow through all the trays.

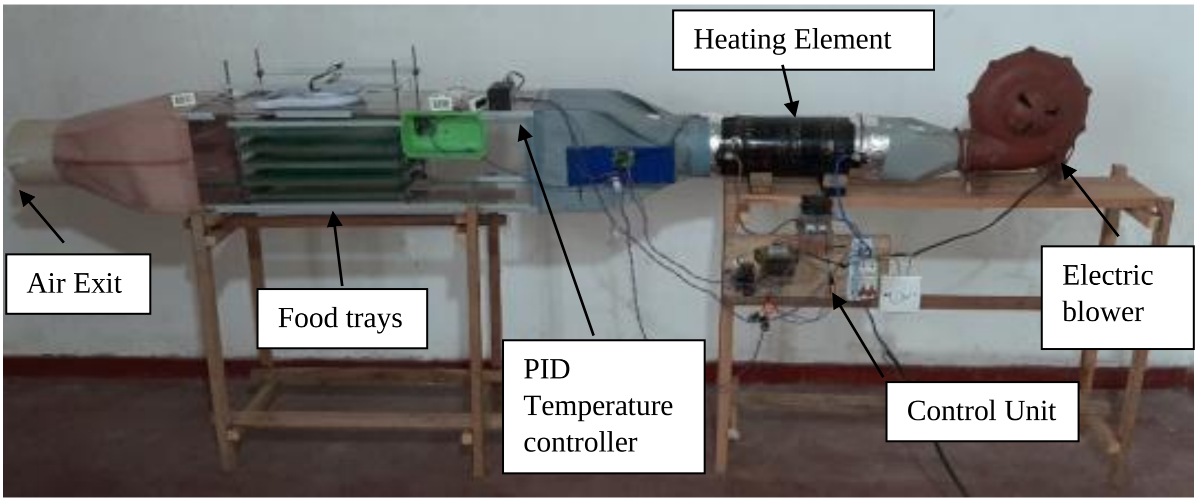

Figure 3.2 - Actual experimental set-ups

The critical dimensions of the experimental setup were kept same as the industrial dryer to get the same drying effect same as the industrial dryer. So that the length of the tray was taken as two feet and the gap between the tray was set to the one inch. A digital weighing scale with a 1g accuracy was installed outside the drying cabin to measure the weight of the tray set. The inlet air temperature to the drying cabin was measured using PT100 temperature sensor coupled with the REX-C100 PID temperature controller. The air velocity was measured using a UT363 turbine type air velocity meter with an accuracy of 0.1 m/s at the exit end. A honeycomb type flow strainer was used to get a uniform laminar flow through all the trays.

3.2.1 Experiment Procedure

It is very important to calculate the initial MC of black pepper and it was determined by a direct method [6]. A known weight of raw black pepper sample was taken and placed inside an electric oven at a temperature of 105 °C to remove all the moisture including the bound water. The sample's weight was measured in every 15 minutes until it became constant. [9]. Equation 2.1 was used to determine the initial MC on a wet basis.

Initially, the dryer was set to achieve a predefined temperature and hot air velocity. The black pepper berries were put on the trays and layered uniformly to get a single layer. Once the dryer reaches to steady-state condition, the trays were loaded onto the tray rack carefully and dried. Temperature and air velocity readings were taken in 120-minute intervals and berries on the trays were properly mixed after each reading. There is a significant essential oil loss when the drying temperature is greater than 65 °C [3]. Drying under 50 °C temperature is not practicable due to higher drying time. So that the experiments were carried out for drying temperatures of

50°C, 55°C, and 60°C, and for drying air velocities of 0.4 m/s, 0.8 m/s, and 1.2 m/s, as shown in Table 3.1.

Table 3.1 – Controlled parameters of the drying experiments carried out

Experiment	Temperature ^{0}C	Hot air velocity m/s
1	60	0.4
2		0.8
3		1.2
4	55	0.4
5		0.8
6		1.2
7	50	0.4
8		0.8
9		1.2

3.3 Determination of air velocity through the food trays

Air velocity measurements were taken at the exits of the tray dryer as shown in Figure 3.3. The air velocities over the food trays were calculated using the Equation 3.1.

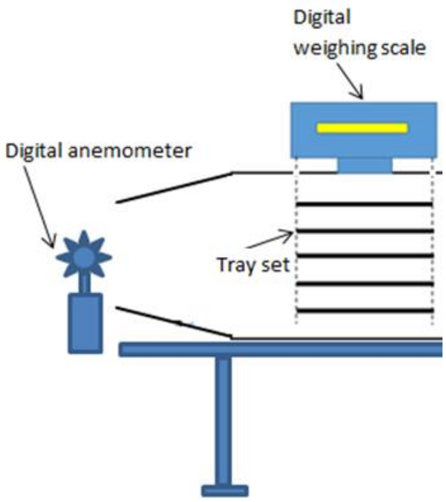

Figure 3.3 - Drying chamber and exit hole

$$u = \frac{V.A}{n.(H-h).w} \qquad 3.1$$

Where,

n	:	Number of trays,
H	:	Height belongs to a tray,
h	:	Height of the tray,
w	:	Width of the tray,
A	:	Exit area,
u	:	Air velocity over the trays,
V	:	Air velocity at the exit end.

3.5 Determination of pepper particle size

pepper particle size was determined by taking the average value of randomly selected two hundred berries, which includes one hundred raw black pepper berries and one hundred dried black pepper berries. A Vernier caliper with an accuracy of 0.05 mm was used to take the measurements. The average size of a pepper particle was found to be 3.8 mm in diameter.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Determine the raw black pepper MC.

The initial MC of a food material can be determined using one of two methods called direct method and the indirect method [6]. direct method was used for the analytical work of this study. Firstly, a 500 g of black pepper sample was placed inside an electric oven and the temperature was set to 105 °C which was used by G.K Jayathunga (2019). Sample weight was measured in every 15 minutes by taking out the sample container from the oven. This was repeated until the weight of the sample become constant. After a 1 hour and 15 minutes, the sample weight became constant, and the sample weight was measured and equals to 176 g. Equation 2.1 was then used to calculate the initial MC on a wet basis and it was found to be 64.8% and it is closely equals to the value presented in P Heartwin Amala Dhas 2001.

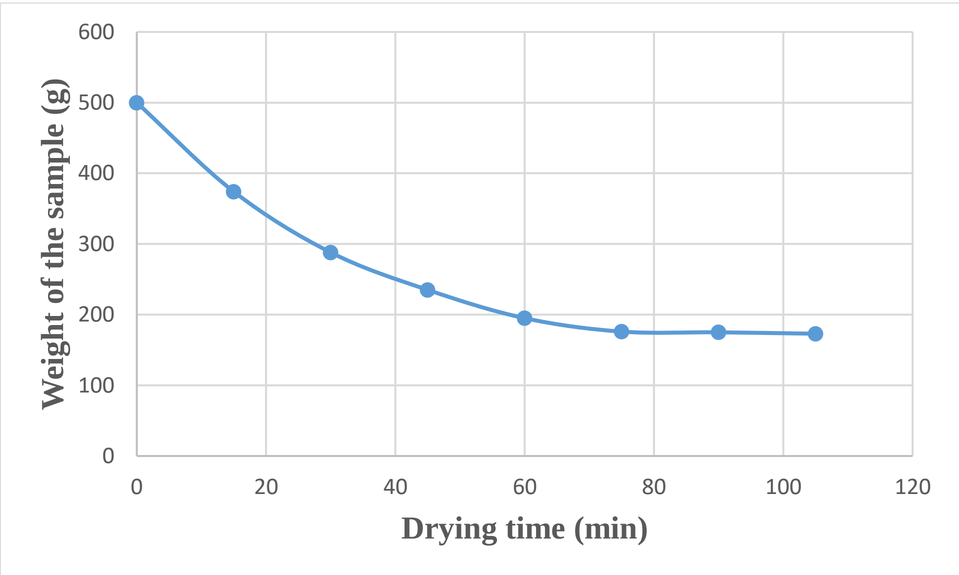

Figure 4.1 – Weight of the sample against drying time

$$MC(wb)_t = \frac{W_t - W_d}{W_t} \times 100$$

$$MC(wb)_t = \frac{500 - 176}{500} \times 100 = 64.8\%$$

4.2 Results from the drying experiments

Experiments were conducted for various hot air temperatures and velocities, as shown in Table 4.1. The sample weight was first recorded after 60 min and then recorded in every 120 min interval of times.

The results obtained from experiments for drying at 60 °C are given in Tables 4.1 to 4.3.

Table 4.1 – Results: Drying Experiment 1

Experiment 1	T - 60 °C, V - 0.4 m/s
Time (min)	Weight of the sample (g)
0	750
60	678
120	617
240	530
360	453
480	388
600	337
690	307

Table 4.2 - Results: Drying Experiment 2

Experiment 2	T - 60 °C, V - 0.8 m/s
Time/ min	Weight of the sample/g
0	750
60	660
120	589
240	489
375	390
480	328
600	280

Table 4.3 - Results: Drying Experiment 3

Experiment 3	T - 60 °C, V – 1.2 m/s
Time/ min	Weight of the sample/g
0	750
60	651
120	581
240	468
300	419
360	377
540	291
600	275

The variation of weight of the sample vs drying time for different drying air velocity and for 60 °C drying temperature is given in Figure 4.2

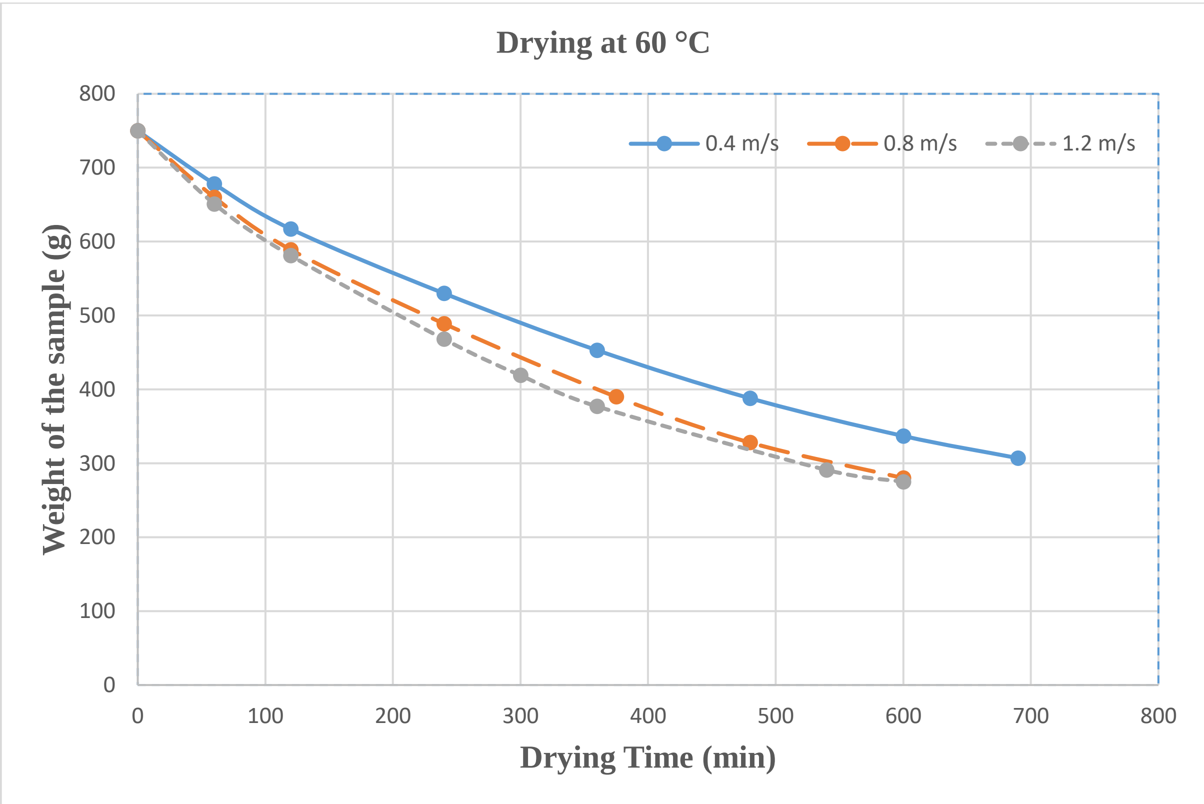

Figure 4.2 – Weight of the sample against drying time for drying at 60 °C

The results obtained from experiments for drying at 55 °C are given in Tables 4.4 to 4.6.

Table 4.4 - Results: Drying Experiment 4

Experiment 4	T - 55 °C, V – 0.4 m/s
Time/ min	Weight of the sample/g
0	750
60	679
120	622
240	538
365	470
480	417
600	369
720	330

Table 4.5 - Results: Drying Experiment 5

Experiment 5	T - 55 °C, V – 0.4 m/s
Time/ min	Weight of the sample/g
0	750
120	623
240	536
360	460
420	424
540	364
660	318
720	303

Table 4.6 - Results: Drying Experiment 6

Experiment 6	T - 55 °C, V – 1.2 m/s
Time/ min	Weight of the sample/g
0	750
60	657
120	599
240	507
360	429
480	364
600	314

The variation of weight of the sample vs drying time for different drying air velocity and for 55°C drying temperature is given in Figure 4.2

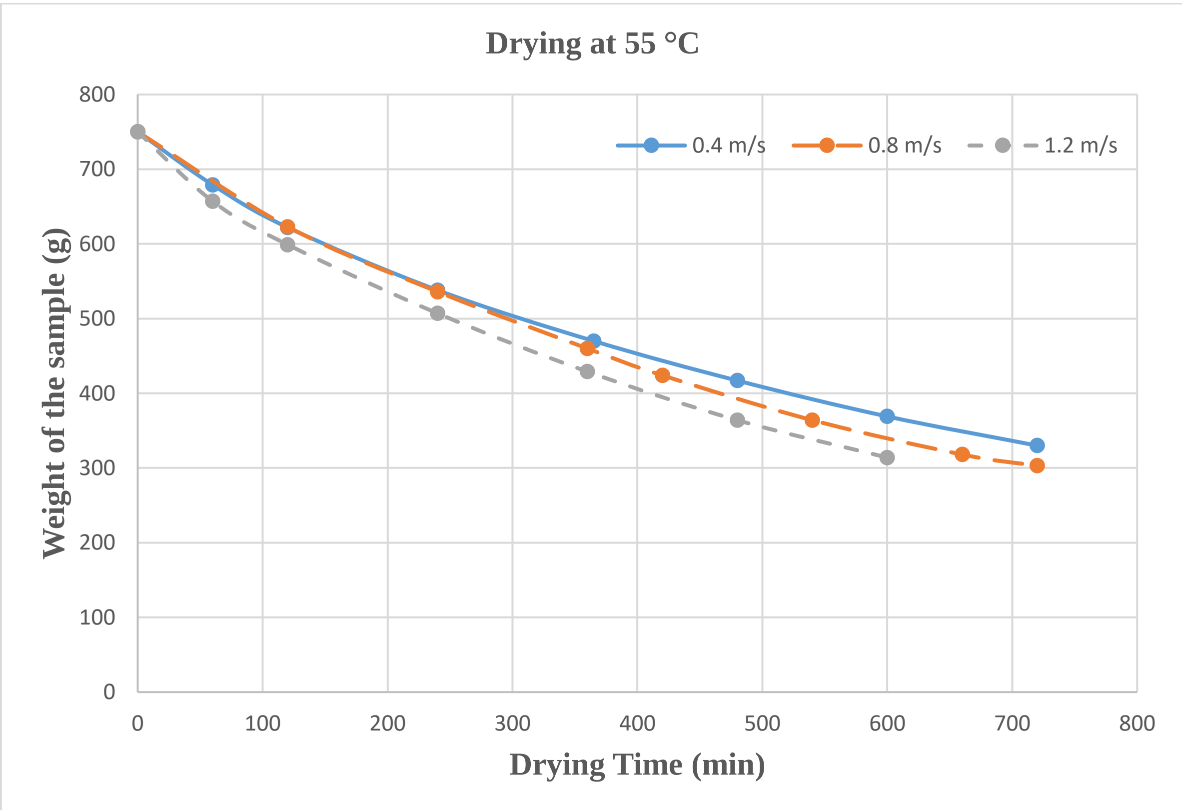

Figure 4.3 – Weight of the sample against drying time for drying at 55 °C

The results obtained from experiments for drying at 50 °C are given in Tables 4.7 to 4.9.

Table 4.7 - Results: Drying Experiment 7

Experiment 7	T - 50 °C, V – 0.4 m/s
Time/ min	Weight of the sample/g
0	750
60	692
120	652
240	584
360	532
510	476
600	447
720	414

Table 4.8 - Results: Drying Experiment 8

Experiment 8	T - 50 °C, V – 0.8 m/s
Time/ min	Weight of the sample/g
0	750
60	686
120	638
240	563
360	508
480	460
600	416
660	398

Table 4.9 - Results: Drying Experiment 9

Experiment 9	T - 50 °C, V – 1.2 m/s
Time/ min	Weight of the sample/g
0	750
60	677
120	626
240	552
360	491
480	436
600	390
660	369

The variation of weight of the sample vs drying time for different drying air velocity and for 50°C drying temperature is given in Figure 4.2

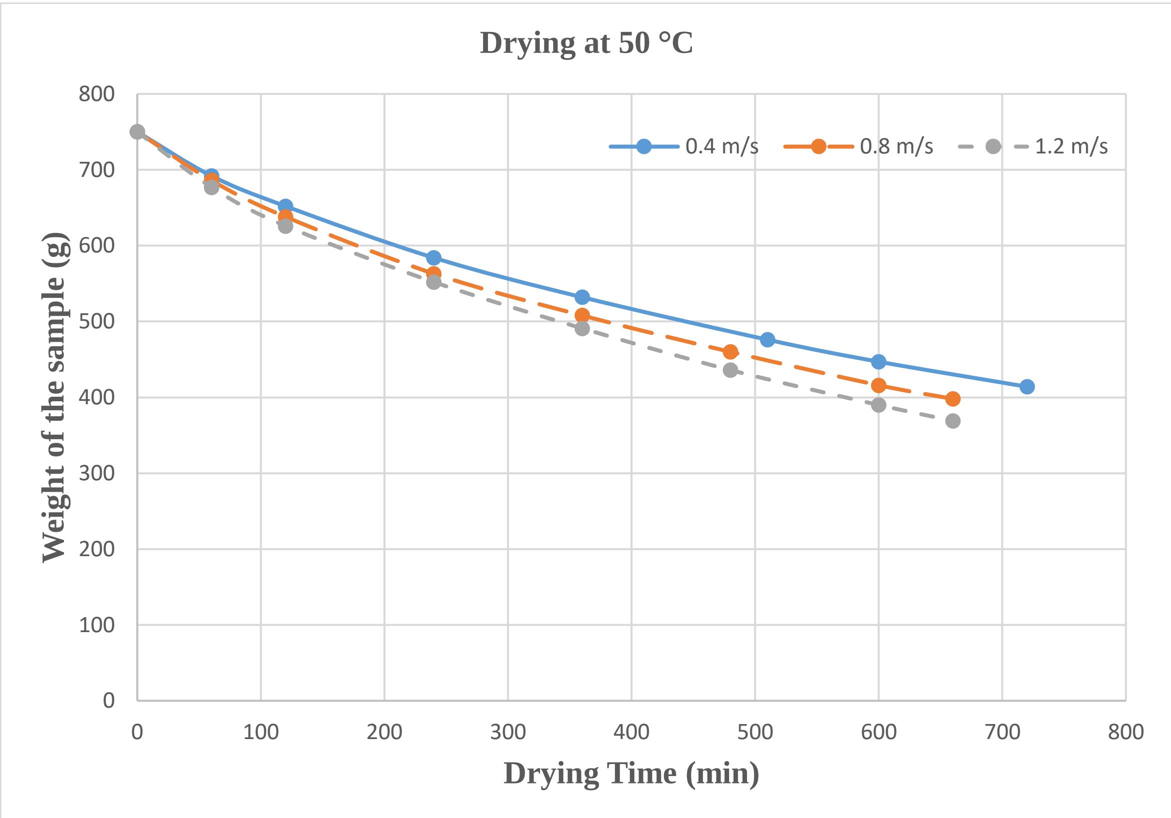

Figure 4.4 – Weight of the sample against drying time for drying at 50 °C

4.3 Selection of best fit DM

4.3.1 Calculation of MR

MRs of each reading was calculated using Equation 2.6, based on the experimentally obtained MC and results are shown in the Table 4.10-4.16.

Table 4.10 - Drying experiments 1, MR values

Experiment 1 Hot air temperature - 60 °C, Hot air velocity - 0.4 m/s		
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	678	0.852
120	617	0.727
240	530	0.549
360	453	0.391
480	388	0.257
600	337	0.153
690	307	0.091

Table 4.11 - Drying experiments 2, MR values

Experiment 2 Hot air temperature - 60 °C, Hot air velocity - 0.8 m/s		
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	660	0.815
120	589	0.670
240	489	0.465
375	390	0.262
480	328	0.134
600	280	0.036

Table 4.12 - Drying experiments 3, MR values

Experiment 3	Hot air temperature - 60 °C, Hot air velocity – 1.2 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	651	0.797
120	581	0.653
240	468	0.422
300	419	0.321
360	377	0.235
540	291	0.058
600	275	0.026

Figure 4.5 shows the MR values obtained as a function of drying time.

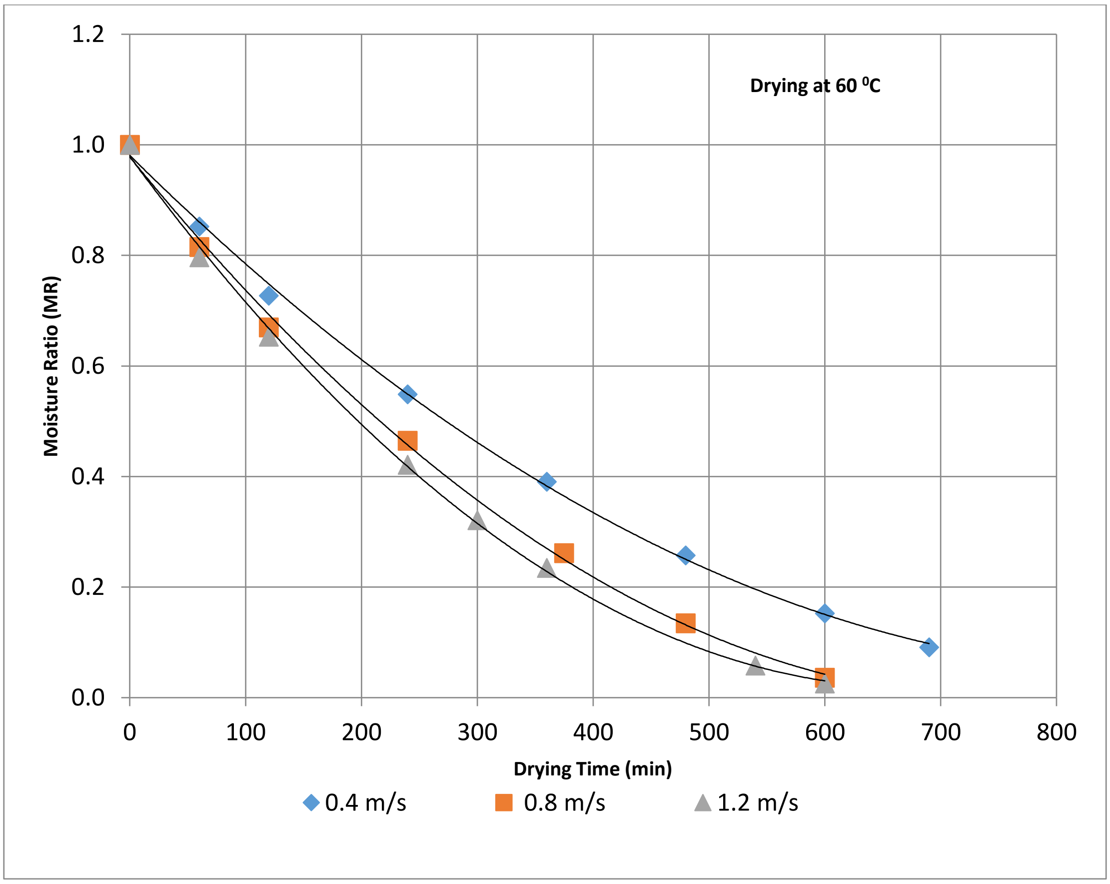

Figure 4.5 - MR against drying time for drying at 60 °C

Table 4.13 - Drying experiments 4, MR values

Experiment 4	Hot air temperature - 55 °C, Hot air velocity – 0.4 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	679	0.854
120	622	0.737
240	538	0.565
365	470	0.426
480	417	0.317
600	369	0.218
720	330	0.138

Table 4.14 - Drying experiments 5, MR values

Experiment 5	Hot air temperature - 55 °C, Hot air velocity – 0.8 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
120	623	0.739
240	536	0.561
360	460	0.405
420	424	0.331
540	364	0.208
660	318	0.114
720	303	0.083

Table 4.15 - Drying experiments 6, MR values

Experiment 6	Hot air temperature - 55 °C, Hot air velocity – 1.2 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	657	0.809
120	599	0.690
240	507	0.502
360	429	0.342
480	364	0.208
600	314	0.106

Figure 4.6 shows the MR values obtained as a function of drying time.

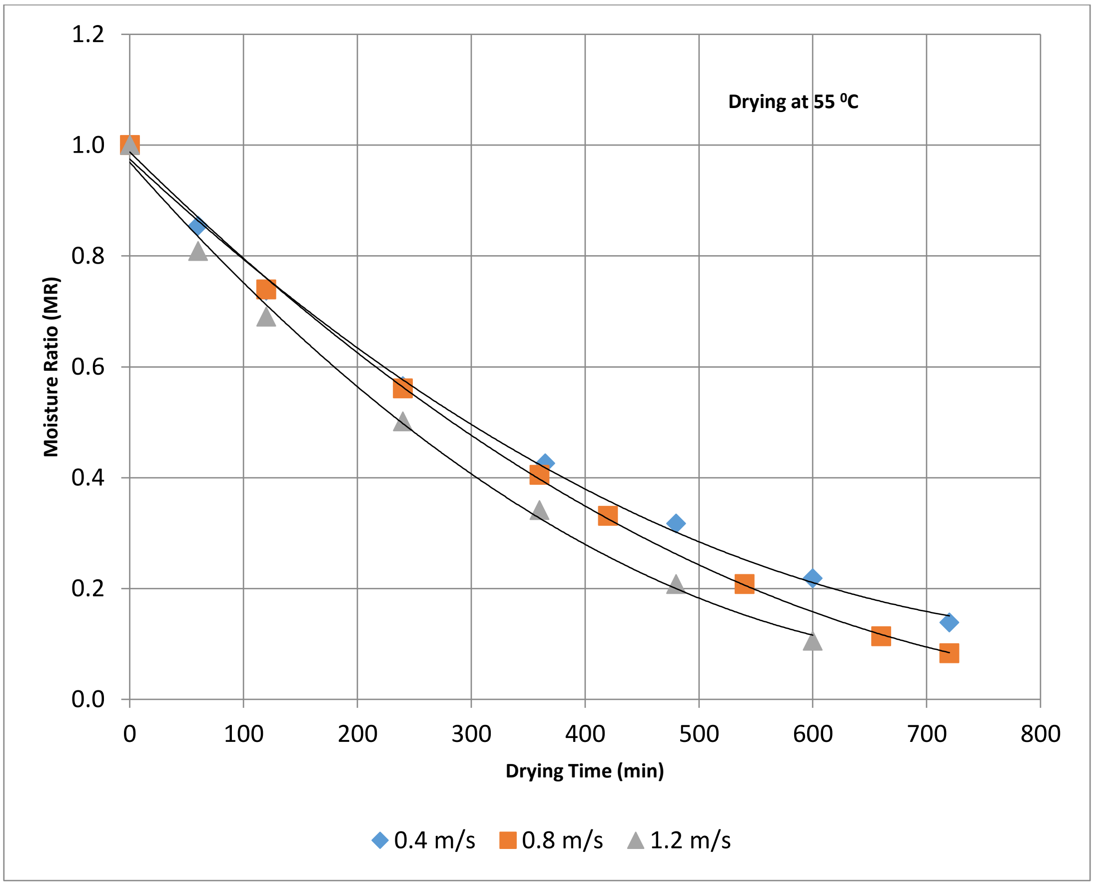

Figure 4.6 - MR against drying time for drying at 55 °C

Table 4.16 - Drying experiments 7, MR values

Experiment 7	Hot air temperature - 50 °C, Hot air velocity – 0.4 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	692	0.881
120	652	0.799
240	584	0.659
360	532	0.553
510	476	0.438
600	447	0.378
720	414	0.311

Table 4.17 - Drying experiments 8, MR values

Experiment 8	Hot air temperature - 50 °C, Hot air velocity – 0.8 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	686	0.869
120	638	0.770
240	563	0.616
360	508	0.504
480	460	0.405
600	416	0.315
660	398	0.278

Table 4.18 - Drying experiments 9, MR values

Experiment 9	Hot air temperature - 50 °C, Hot air velocity – 1.2 m/s	
Time(min)	Weight of the sample (g)	Moisture ratio (MR)
0	750	1.000
60	677	0.850
120	626	0.746
240	552	0.594
360	491	0.469
480	436	0.356
600	390	0.262
660	369	0.218

Figure 4.7 shows the MR values obtained as a function of drying time.

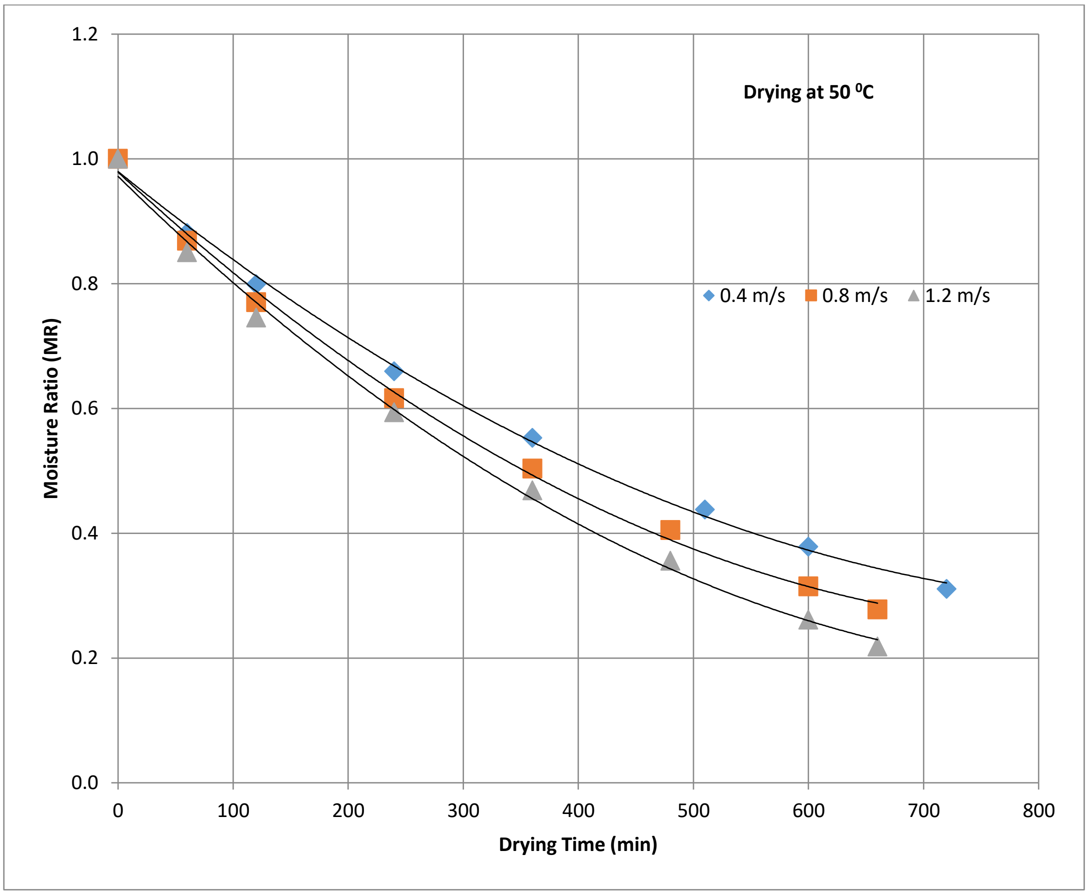

Figure 4.7 – MR against drying time for drying at 50 °C

The relationship between MR and drying time for hot air temperatures of 50°C, 55°C, and 60°C and air velocity of 0.4 m/s is given in Figure 4.8

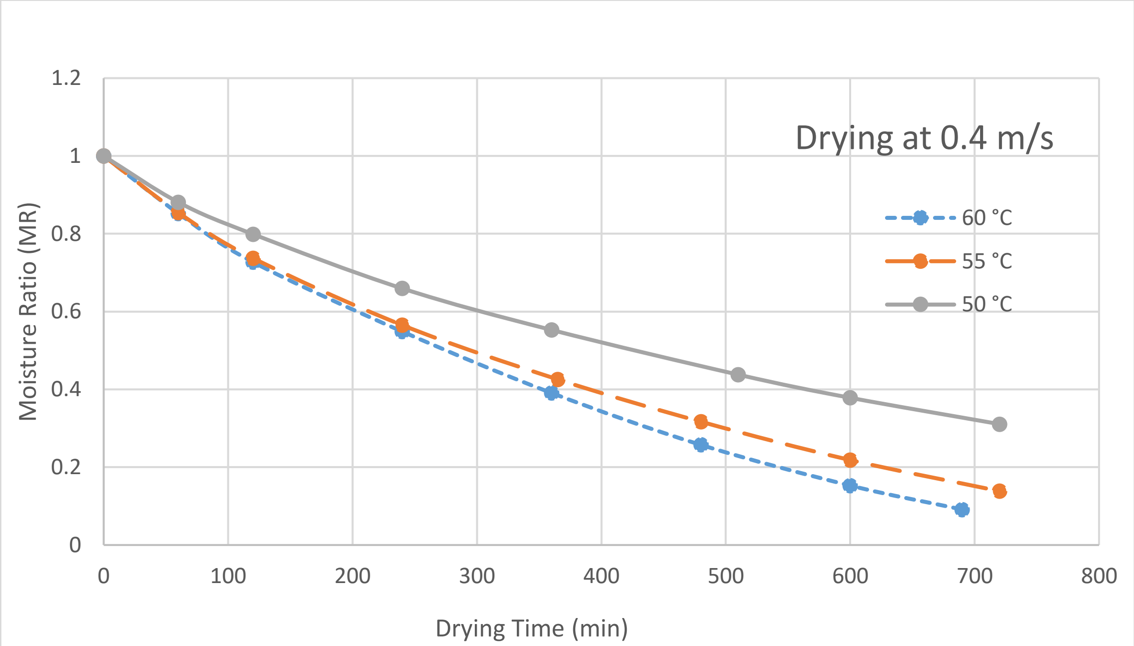

Figure 4.8 – MR against drying time for drying at 0.4 m/s

The relationship between MR and drying time for hot air temperatures of 50°C, 55°C, and 60°C and air velocity of 0.8 m/s is given in Figure 4.9.

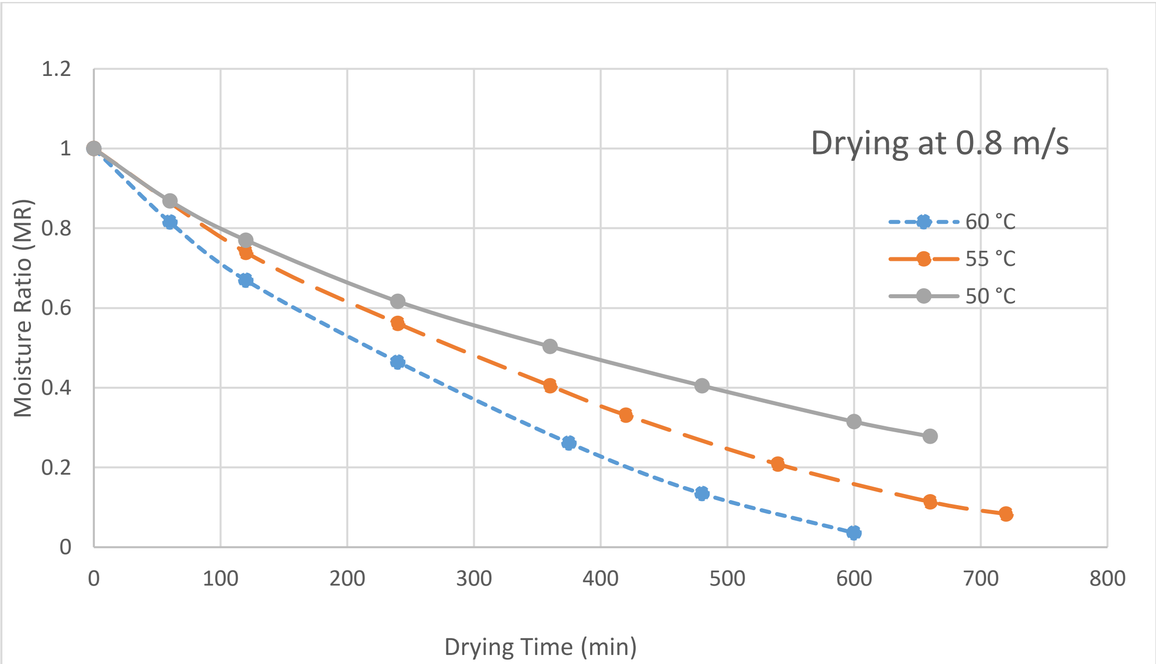

Figure 4.9 – MR against drying time for drying at 0.8 m/s

The relationship between MR and drying time for hot air temperatures of 50°C, 55°C, and 60°C and an air velocity of 1.2 m/s is given in Figure 4.10.

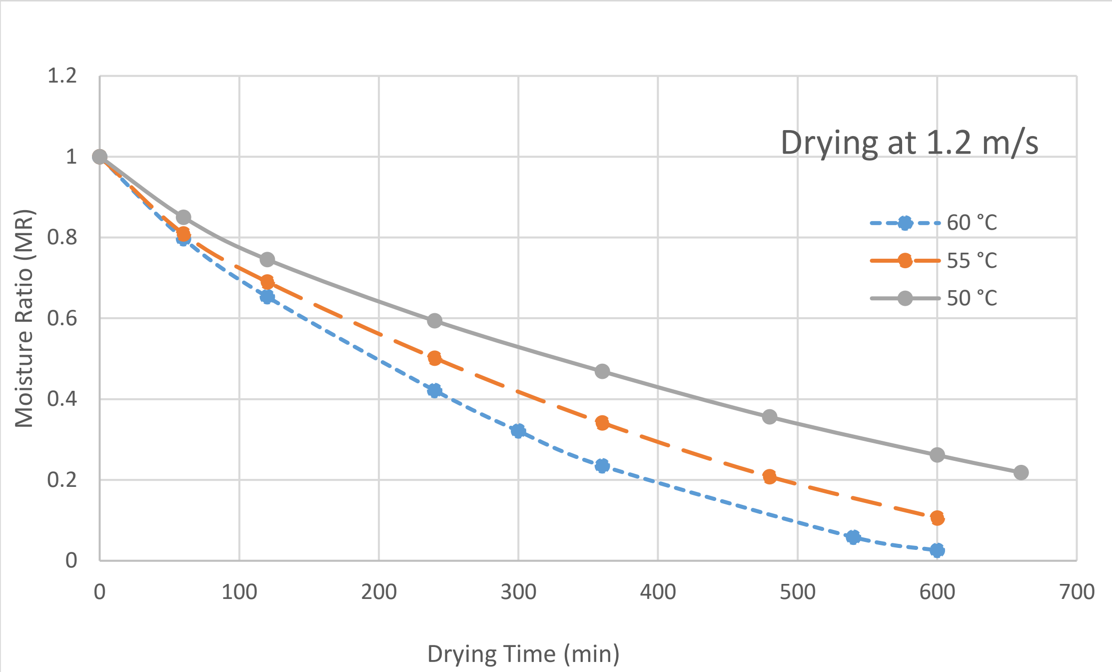

Figure 4.10 – MR against drying time for drying at 1.2 m/s

According to the results shown in Figure 4.5, Figure 4.6 and Figure 4.7 total drying time reduces when increasing the hot air velocity for any hot air temperature. According to the results shown in Figure 4.8, Figure 4.9 and Figure 4.10 total drying time reduces when increasing the hot air temperature for any hot air velocity.

4.3.2 Experimental data fitting with DMs

MR vales were fitted using MS Excel with the six popular DM. To find the best-fit DM and its constants, the Minimum Root Mean Square Error (RMSE) approach was used. The results obtained the analysis is summarized in Tables 4.19-4.21 for different temperatures.

Table 4.19 - Statistical analysis of data fitting for drying at T=50 ^{0}C

Model	Air Velocity (ms^{-1})	Coefficients	$RMSE$
Newton	0.4	k=0.001655	0.013116
	0.8	k=0.001947	0.012408
	1.2	k=0.002217	0.014782
Page	0.4	k=0.002779, n=0.915040	0.005051
	0.8	k=0.002955, n=0.930795	0.006986
	1.2	k=0.002785, n=0.961889	0.013585
Henderson & Pabis	0.4	a=0.981744, k= 0.001606	0.009194
	0.8	a=0.983972, k= 0.001901	0.009497
	1.2	a=0.986407, k= 0.002175	0.013203
Two-term exponential	0.4	a=0.965467, b=0.034533, k_0=0.001563, k_1=180.0798	0.002366
	0.8	a=0.968001, b= 0.032000, k_0=0.001855, k_1=184.2981	0.005097
	1.2	a=0.971770, b= 0.028230, k_0=0.002131, k_1=193.9786	0.011236
Midilli et al.	0.4	a=0.995974, n= 0.924109, k= 0.002613, b=0.000000	0.004819
	0.8	a=0.995855, n= 0.939508, k= 0.002787, b=0.000000	0.006815
	1.2	a=0.989859, n= 0.983003, k= 0.002420, b=0.000000	0.013067
Logarithmic	0.4	a=0.910402, c= 0.0774243, k= 0.001851	0.007745
	0.8	a=0.945327, c= 0.0424782, k= 0.002058	0.008975
	1.2	a=0.986407, c= 0.0000000, k= 0.002117	0.013203

Table 4.20 - Statistical analysis of data fitting for drying at T=55 ^{0}C

Model	Air Velocity (ms^{-1})	Coefficients	$RMSE$
Newton	0.4	k=0.002466	0.014876
	0.8	k=0.002741	0.034485
	1.2	k=0.003150	0.023903
Page	0.4	k=0.002133, n= 1.024381	0.014360
	0.8	k=0.000799, n=1.205616	0.020036
	1.2	k=0.002407, n=1.046887	0.022682
Henderson & Pabis	0.4	a=0.999260, k= 0.002464	0.014872
	0.8	a=1.024498, k= 0.002809	0.032994
	1.2	a=1.000007, k= 0.003150	0.023903
Two-term exponential	0.4	a=0.998390, b= 0.001609, k_0=0.002461, k_1=204.8126	0.014867
	0.8	a=1.024498, b= 0.000000, k_0=0.002809, k_1=265.7229	0.032994
	1.2	a=1.000007, b= 0.000000, k_0=0.003150, k_1=176.8645	0.023903
Midilli et al.	0.4	a=0.989890, n= 1.045146, k= 0.001860, b=0.000000	0.013866
	0.8	a=0.987631, n= 1.228352, k= 0.000688, b=0.000000	0.019547
	1.2	a=0.984532, n= 1.078167, k= 0.001971, b=0.000000	0.021894
Logarithmic	0.4	a=0.999259, c= 0.0000000, k= 0.002464	0.014872
	0.8	a=1.024499, c=0.0000000, k= 0.002809	0.032994
	1.2	a=1.000007, c= -0.000000, k= 0.003150	0.023903

Table 4.21 - Statistical analysis of data fitting for drying at T=60 ^{0}C

Model	Air Velocity (ms^{-1})	Coefficients	$RMSE$
Newton	0.4	k=0.002801	.028122
	0.8	k=0.003659	0.038571
	1.2	k=0.003973	0.036448
Page	0.4	k=0.001330, n= 1.126257	0.020084
	0.8	k=0.001432, n=1.165568	0.028018
	1.2	k=0.001527, n=1.170115	0.025741
Henderson & Pabis	0.4	a=1.016252, k= 0.002855	0.027058
	0.8	a=1.021308, k= 0.003750	0.037221
	1.2	a=1.021001, k= 0.004063	0.035265
Two-term exponential	0.4	a=1.016253, b= 0.000000, k_0=204.8451, k_1=0.002855	0.027058
	0.8	a=1.021309, b= 0.000000, k_0=0.003750, k_1=1.007900	0.037221
	1.2	a=1.021002, b= 0.000000, k_0=0.004063, k_1=1.007900	0.035265
Midilli et al.	0.4	a=0.983319, n= 1.163730, k= 0.001043, b=0.000000	0.018234
	0.8	a=0.980000, n= 1.204375, k= 0.001123, b=0.000000	0.027180
	1.2	a=0.980000, n= 1.211107, k= 0.001184, b=0.000000	0.024753
Logarithmic	0.4	a=1.236616, c= -0.2465186, k= 0.001873	0.007791
	0.8	a=1.276342, c= -0.2873870, k= 0.002281	0.009795
	1.2	a=1.200493, c= -0.2083005, k= 0.002748	0.006778

The lowest RMSE value was used to select the best-fit DM for black pepper. The logarithmic DM was the best-fitting DM out of the other six models which can be used to predict the MR of the black pepper drying in a tray dryer. Only the logarithmic model fitting details are given in this chapter.

4.3.3 Details of the experimentally obtained data fitting with logarithmic DM for drying at 50 ^{0}C temperature and 0.4m/s air velocity

The data gained from the drying experiment at 50 ^{0}C and air velocity of 0.4 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.22, Table 4.23, and Figure 4.11

Table 4.22 - Logarithmic model parameters for drying at 50°C and 0.4m/s

Logarithmic Drying model constants			
a =	0.910402	c =	0.06
k =	0.001851		

Table 4.23 – Data fitting details for 50 ^{0}C & 0.4 m/s

Test 50 ^{0}C & 0.4m/s				
Time (min)	Weight (g)	Experimentally obtained MR at 0.4 m/s	Logarithmic model Predicted MR at 0.4 m/s	Square Error
0	750	1.000000	0.970402	0.000876
60	692	0.881026	0.874721	0.000040
120	652	0.798974	0.789096	0.000098
240	584	0.659487	0.643897	0.000243
360	532	0.552821	0.527615	0.000635
510	476	0.437949	0.414265	0.000561
600	447	0.378462	0.359911	0.000344
720	414	0.310769	0.300184	0.000112
			RMSE	0.019069

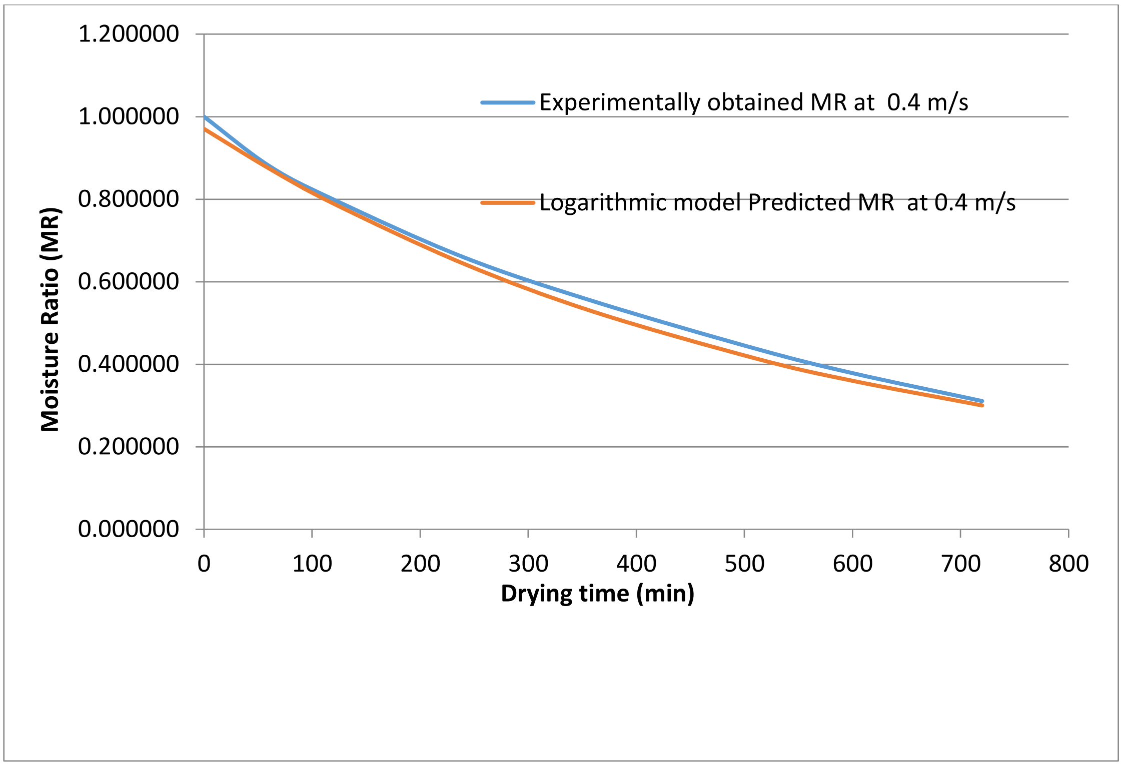

Figure 4.11 – MR vs. drying time at 50°C and 0.4m/s drying

4.3.4 Details of the experimentally obtained data fitting with logarithmic DM for drying at 50 ^{0}C temperature and 0.8m/s air velocity

The data gained from the drying experiment at hot air temperature of 50 ^{0}C and 0.8 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.24, Table 4.25, and Figure 4.12

Table 4.24 - Logarithmic model parameters for drying at 50°C and 0.8m/s

Logarithmic Drying model constants			
a =	0.945327	c =	0.042478266
k =	0.002058		

Table 4.25 - Data fitting details for 50 ^{0}C & 0.8m/s

Test 50 ^{0}C & 0.8m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 0.8 m/s	Logarithmic model Predicted MR at 0.8 m/s	Square Error
0	750	1.000000	0.987805	0.000149
60	686	0.868718	0.878008	0.000086
120	638	0.770256	0.780963	0.000115
240	563	0.616410	0.619379	0.000009
360	508	0.503590	0.493151	0.000109
480	460	0.405128	0.394542	0.000112
600	416	0.314872	0.317509	0.000007
660	398	0.277949	0.285565	0.000058
			RMSE	0.008975

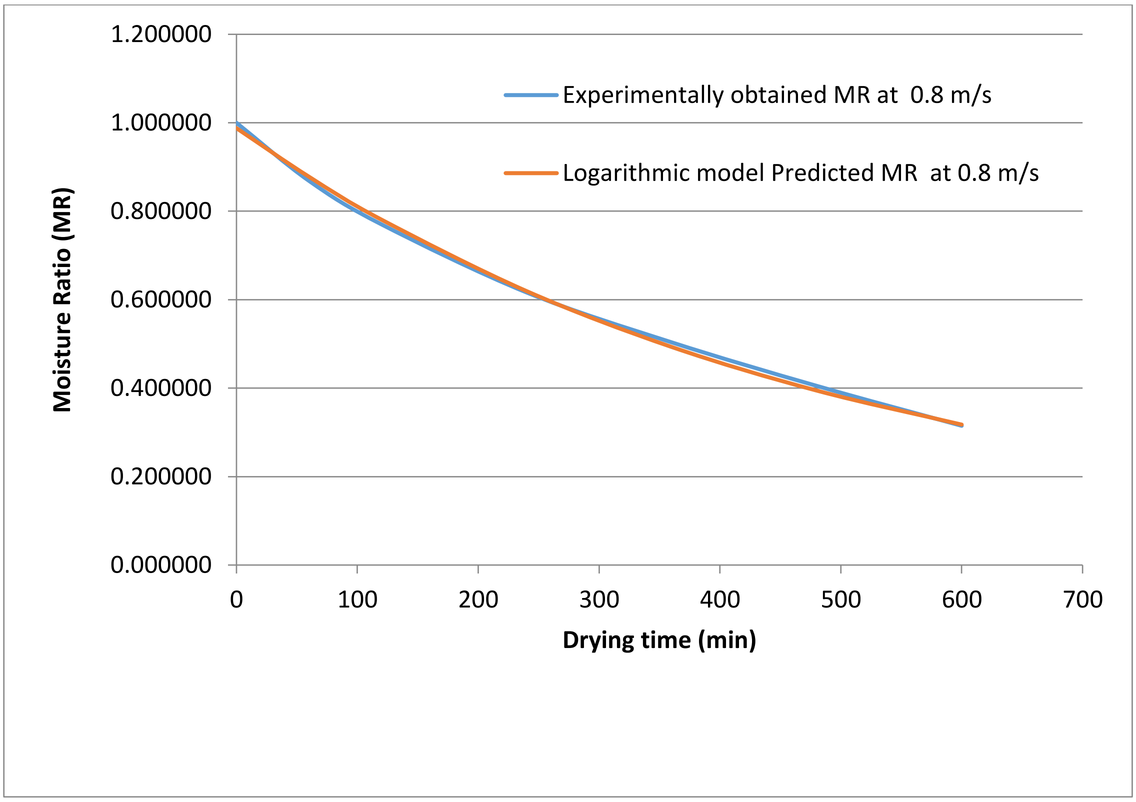

Figure 4.12 - MR vs. drying time at 50°C and 0.8 m/s drying

4.3.5 Details of the experimentally obtained data fitting with logarithmic DM for drying at 50 ^{0}C temperature and 1.2 m/s air velocity

The data gained from the drying experiment at hot air temperature of 50 ^{0}C and 1.2 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.26, Table 4.27, and Figure 4.13

Table 4.26 - Logarithmic model parameters for drying at 50°C and 1.2 m/s

Logarithmic Drying model constants			
a =	0.986407	c =	0
k =	0.002175		

Table 4.27 - Data fitting details for 50 ^{0}C & 1.2 m/s

Test 50 ^{0}C & 1.2m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 1.2 m/s	Logarithmic model Predicted MR at 1.2 m/s	Square Error
0	750	1.000000	0.986407	0.000185
60	677	0.850256	0.865716	0.000239
120	626	0.745641	0.759793	0.000200
240	552	0.593846	0.585240	0.000074
360	491	0.468718	0.450789	0.000321
480	436	0.355897	0.347226	0.000075
600	390	0.261538	0.267456	0.000035
660	369	0.218462	0.234732	0.000265
			RMSE	0.013203

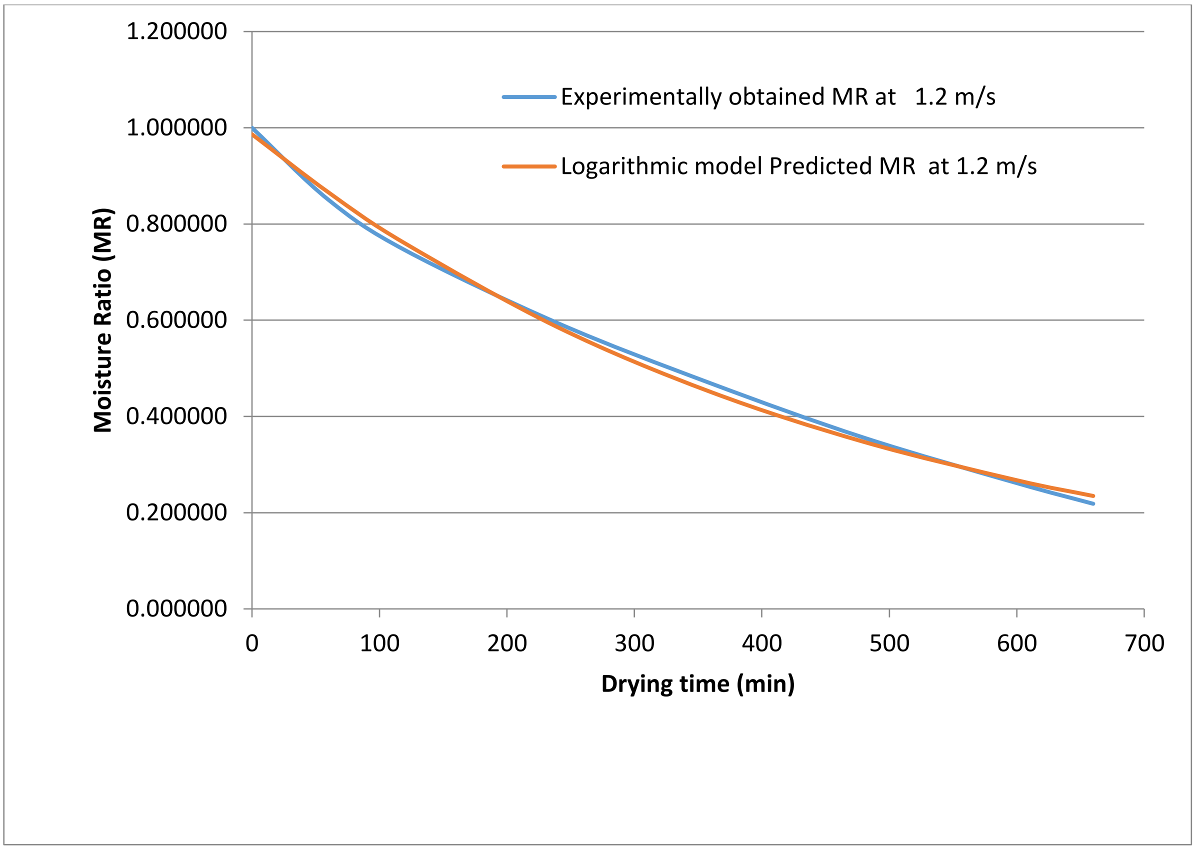

Figure 4.13 – MR vs. drying time at 50°C and 1.2 m/s drying

4.3.6 Details of the experimentally obtained data fitting with logarithmic DM for drying at 55 ^{0}C temperature and 0.4 m/s air velocity

The data gained from the drying experiment at hot air temperature of 55 ^{0}C and 0.4 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.28, Table 4.29, and Figure 4.14

Table 4.28 - Logarithmic model parameters for drying at 55 °C and 0.4 m/s

Logarithmic Drying model constants			
a =	0.999259	c =	0.000000
k =	0.002464		

Table 4.29 - Data fitting details for 55 ^{0}C & 0.4 m/s

Test 55 ^{0}C & 0.4m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 0.4 m/s	Logarithmic model Predicted MR at 0.4 m/s	Square Error
0	750	1.000000	0.999259	0.000001
60	679	0.854359	0.861928	0.000057
120	622	0.737436	0.743471	0.000036
240	538	0.565128	0.553159	0.000143
365	470	0.425641	0.406524	0.000365
480	417	0.316923	0.306212	0.000115
600	369	0.218462	0.227829	0.000088
720	330	0.138462	0.169510	0.000964
			RMSE	0.014872

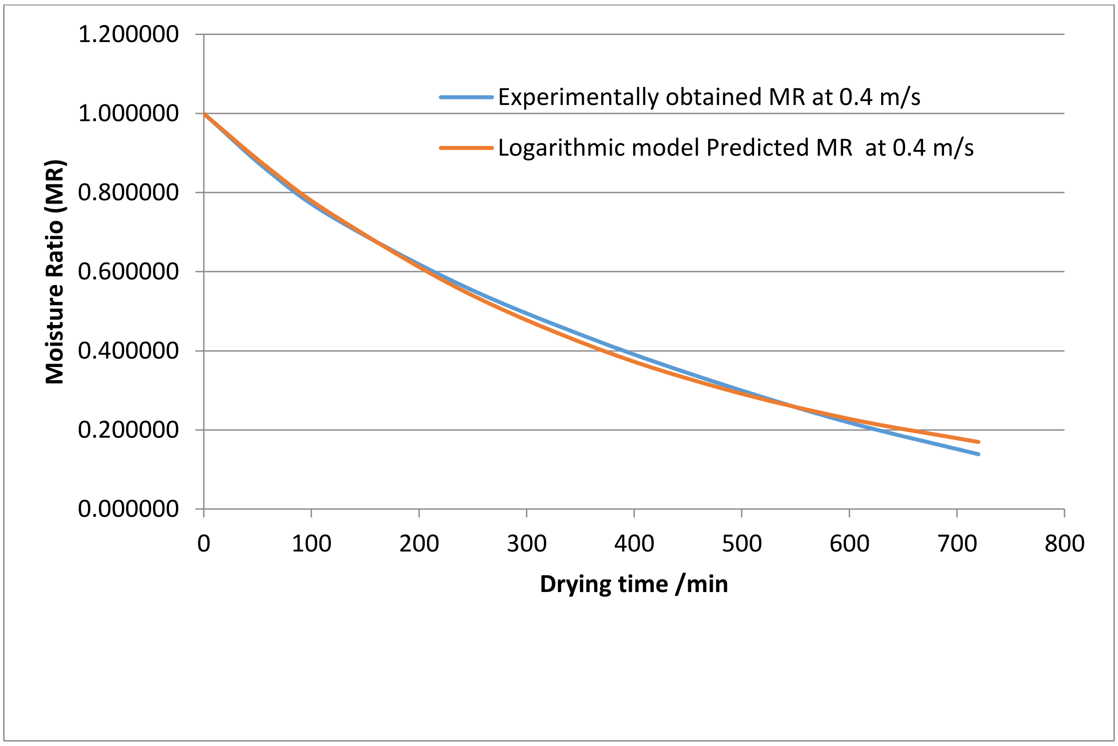

Figure 4.14 – MR vs. drying time at 55°C and 0.4m/s drying

4.3.7 Details of the experimentally obtained data fitting with logarithmic DM for drying at 55 ^{0}C temperature and 0.8 m/s air velocity

The data gained from the drying experiment at hot air temperature of 50 ^{0}C and 0.8 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.30, Table 4.31, and Figure 4.15

Table 4.30 - Logarithmic model parameters for drying at 55 °C and 0.8 m/s

Logarithmic Drying model constants			
a =	1.024499	c =	0
k =	0.002809		

Table 4.31 - Data fitting details for 55C & 0.8 m/s

Test 55 ^{0}C & 0.8 m/s				
Tine (min)	Weight (g)	Moisture ratio from experiment 0.8 m/s	Logarithmic model Predicted MR at 0.8 m/s	Square Error
0	750	1.000000	1.024499	0.000600
120	623	0.739487	0.731383	0.000066
240	536	0.561026	0.522130	0.001513
360	460	0.405128	0.372746	0.001049
420	424	0.331282	0.314941	0.000267
540	364	0.208205	0.224834	0.000277
660	318	0.113846	0.160508	0.002177
720	303	0.083077	0.135617	0.002760
			RMSE	0.032994

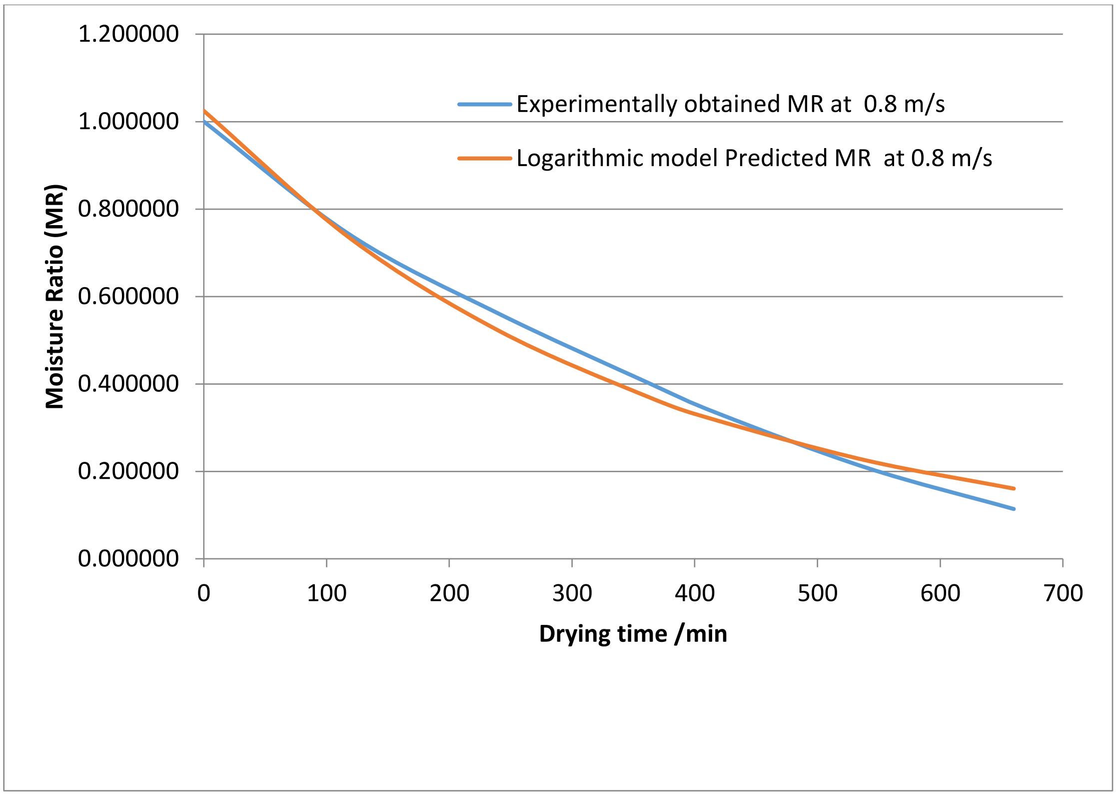

Figure 4.15 – MR vs. drying time at 55°C and 0.8m/s drying

4.3.8 Details of the experimentally obtained data fitting with logarithmic DM for drying at 55 ^{0}C temperature and 1.2 m/s air velocity

The data gained from the drying experiment at hot air temperature of 50 ^{0}C and 1.2 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.32, Table 4.33, and Figure 4.16

Table 4.32 - Logarithmic model parameters for drying at 55 °C and 1.2 m/s

Logarithmic Drying model constants			
a =	1.000007	c =	0
k =	0.003150		

Table 4.33 - Data fitting details for 55 ^{0}C & 1.2 m/s

Test 55 ^{0}C & 1.2m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 1.2 m/s	Logarithmic model Predicted MR at 1.2 m/s	Square Error
0	750	1.000000	1.000007	0.000000
60	657	0.809231	0.827768	0.000344
120	599	0.690256	0.685196	0.000026
240	507	0.501538	0.469490	0.001027
360	429	0.341538	0.321690	0.000394
480	364	0.208205	0.220419	0.000149
600	314	0.105641	0.151029	0.002060
			RMSE	0.023903

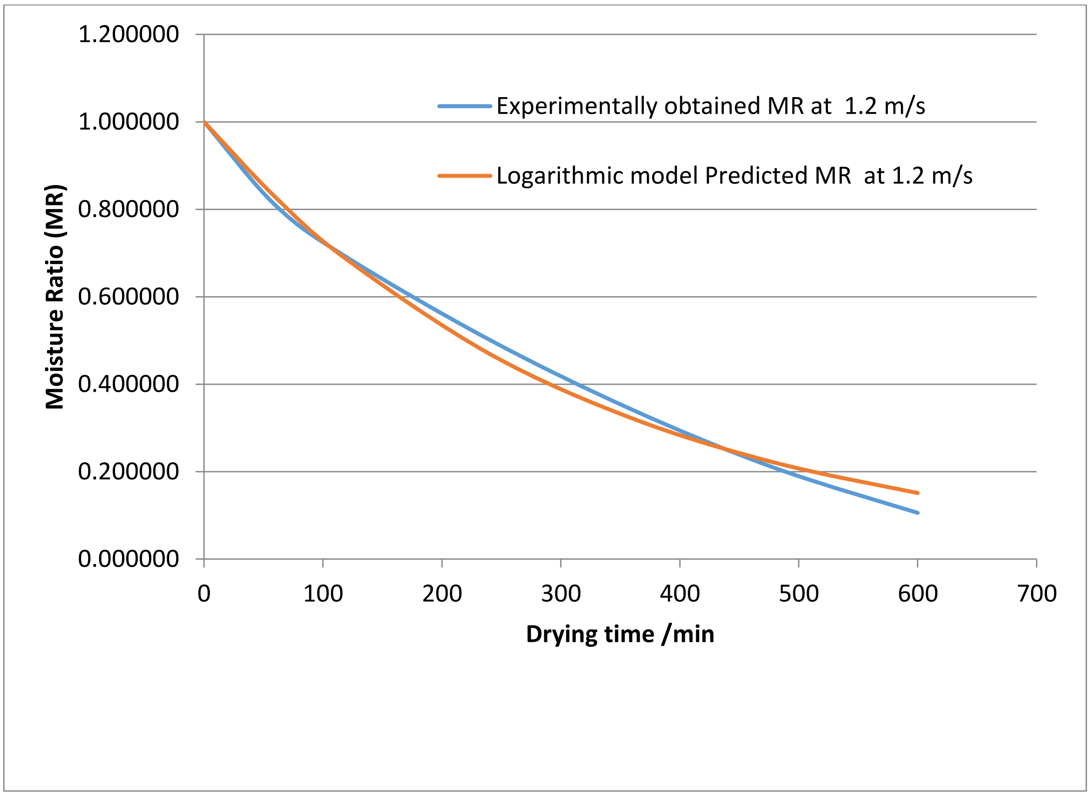

Figure 4.16 - MR vs. drying time at 55°C and 1.2 m/s drying

4.3.9 Details of the experimentally obtained data fitting with logarithmic DM for drying at 60 °C temperature and 0.4 m/s air velocity

The data gained from the drying experiment at hot air temperature of 60 ^{0}C and 0.4 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.34, Table 4.35, and Figure 4.17

Table 4.34 - Logarithmic model parameters for drying at 60 °C and 0.4 m/s

Logarithmic Drying model constants			
a =	1.236616	c =	-0.246518654
k =	0.001873		

Table 4.35 - Data fitting details for 60 °C & 0.4 m/s

Test 60 ^{0}C & 0.4 m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 0.4 m/s	Logarithmic model Predicted MR at 0.4 m/s	Square Error
0	750	1.000000	0.990097	0.000098
60	678	0.852308	0.858621	0.000040
120	617	0.727179	0.741123	0.000194
240	530	0.548718	0.542277	0.000041
360	453	0.390769	0.383465	0.000053
480	388	0.257436	0.256627	0.000001
600	337	0.152821	0.155326	0.000006
690	307	0.091282	0.092975	0.000003
			RMSE	0.007391

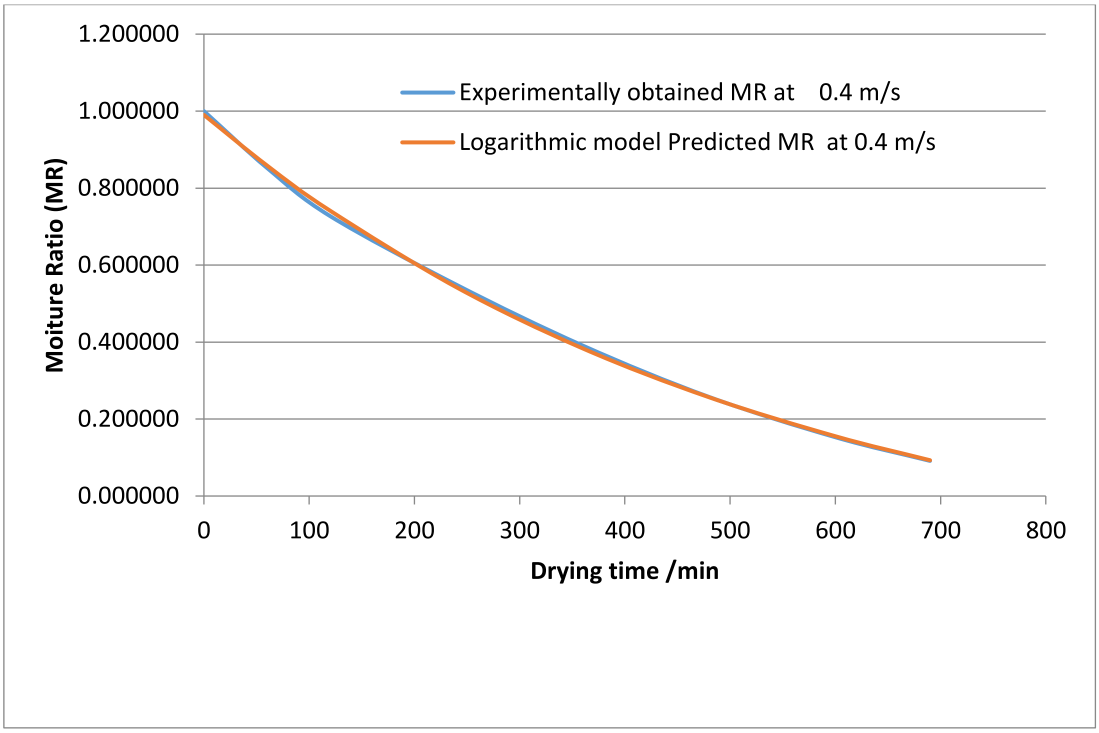

Figure 4.17 – MR vs. drying time at 60°C and 0.4m/s drying

4.3.10 Details of the experimentally obtained data fitting with logarithmic DM for drying at 60 °C temperature and 0.8 m/s air velocity

The data gained from the drying experiment at hot air temperature of 60 ^{0}C and 0.8 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.36, Table 4.37, and Figure 4.18

Table 4.36 - Logarithmic model parameters for drying at 60 °C and 0.8 m/s

Logarithmic Drying model constants			
a =	1.276342	c =	-0.287387025
k =	0.002281		

Table 4.37 - Data fitting details for 60 °C & 0.8 m/s

Test 60 ^{0}C & 0.8 m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 0.8 m/s	Logarithmic model Predicted MR at 0.8 m/s	Square Error
0	750	1.000000	0.988955	0.000122
60	660	0.815385	0.825729	0.000107
120	589	0.669744	0.683377	0.000186
240	489	0.464615	0.450960	0.000186
375	390	0.261538	0.255302	0.000039
480	328	0.134359	0.139737	0.000029
600	280	0.035897	0.037476	0.000002
			RMSE	0.009795

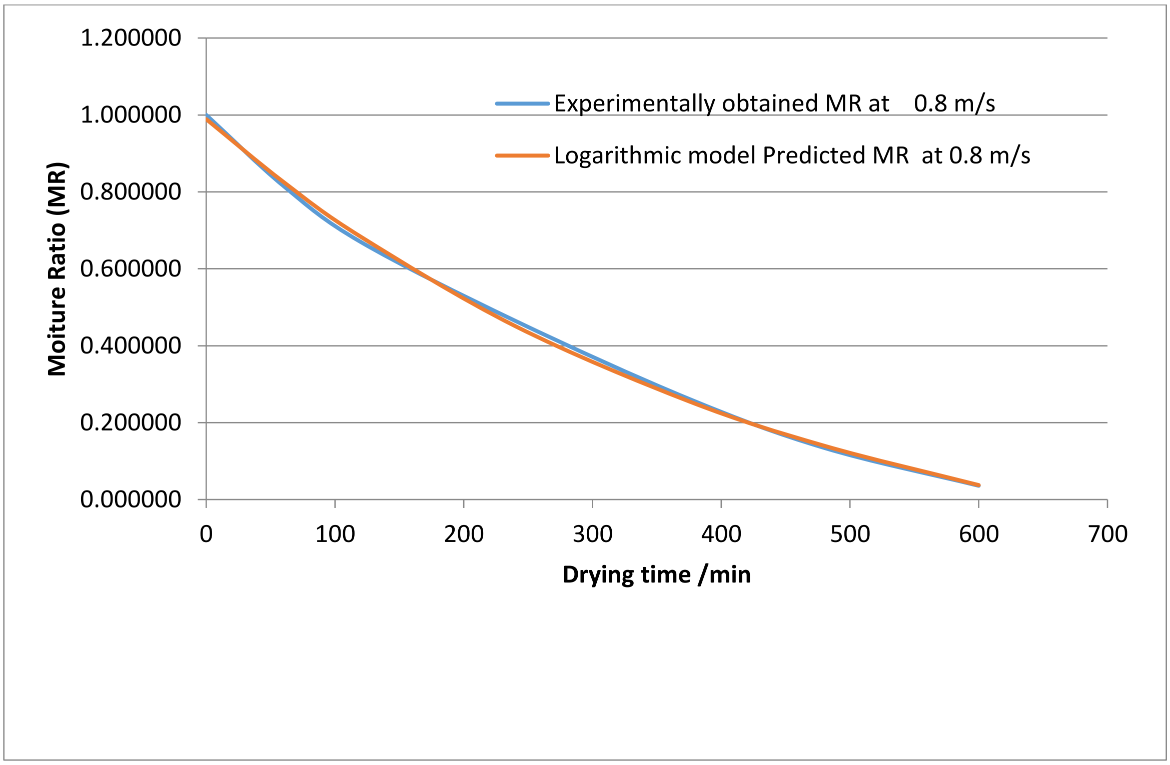

Figure 4.18 – MR vs. drying time at 60°C and 0.8 m/s drying

4.3.11 Details of the experimentally obtained data fitting with logarithmic DM for drying at 60 °C temperature and 1.2 m/s air velocity

The data gained from the drying experiment at hot air temperature of 60 ^{0}C and 1.2 m/s were fitted with the logarithmic DM using the MS Excel solver. The results obtained is shown in Table 4.38, Table 4.39, and Figure 4.19

Table 4.38 - Logarithmic model parameters for drying at 60 °C and 1.2 m/s

Logarithmic Drying model constants			
a =	1.200493	c =	-0.208300502
k =	0.002748		

Table 4.39 - Data fitting details for 60 °C & 1.2 m/s

Test 60 ^{0}C & 1.2m/s				
Time (min)	Weight (g)	Moisture ratio from experiment 0.4 m/s	Logarithmic model Predicted MR at 0.4 m/s	Square Error
0	750	1.000000	0.992192	0.000061
60	651	0.796923	0.809699	0.000163
120	581	0.653333	0.654947	0.000003
240	468	0.421538	0.412442	0.000083
300	419	0.321026	0.318079	0.000009
360	377	0.234872	0.238062	0.000010
540	291	0.058462	0.063876	0.000029
600	275	0.025641	0.022501	0.000010
			RMSE	0.006778

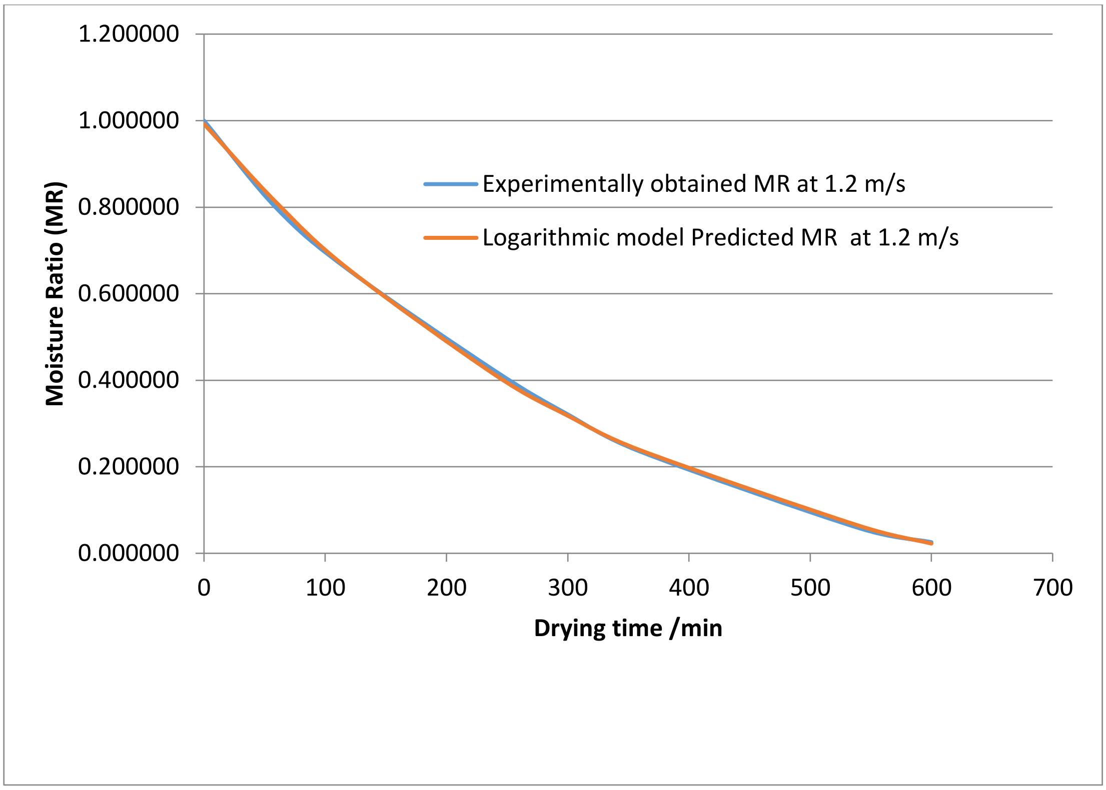

Figure 4.19 - MR vs. drying time at 60°C and 1.2 m/s drying

4.4 Calculation of the total Drying time

The total time taken to reduce the MC of the black pepper to a recommended optimum safe storage limit (MC equals to 12% in dry basis [6]) in drying is called the drying time.

4.4.1 Calculation of MR at optimum safe storage limit

In section 4.1, the raw black pepper MC was found to be 64.8% in wet basis. The equivalent dry basis MC is equals to 185.71%. The MR value at MCs equal to 12% was calculated using Equation 2.28 as follows.

$$MR_T = \frac{MC(db)_{t=T}}{MC(db)_{t=0}} = \frac{12\%}{185.71\%} = 0.0646$$

4.4.2 Calculation of total drying time

Then the total drying time was calculated using the Logarithmic model equation (Equation 2.17) as follows.

$$T = \frac{\ln\left(\frac{MR_T - c}{a}\right)}{-k}$$

Hence the calculated drying times are listed in Table 4.40

Table 4.40 **-** Total drying time for the different temperatures and air velocities.

Temperature	Hot air velocity	Drying time	Drying time
60	0.4	736.59	12 hr 16 min
60	0.8	564.84	9 hr 24 min
60	1.2	539.03	8 hr 58 min
55	0.4	1111.51	18 hr 31min
55	0.8	984.06	16 hr 24 min
55	1.2	869.56	14 hr 29 min
50	0.4	2857.25	47 hr 37 min
50	0.8	1824.80	30 hr 24 min
50	1.2	1253.16	20 hr 52 min

The total drying time reduces when increasing the temperature and air velocity as presented in Figure 4.20

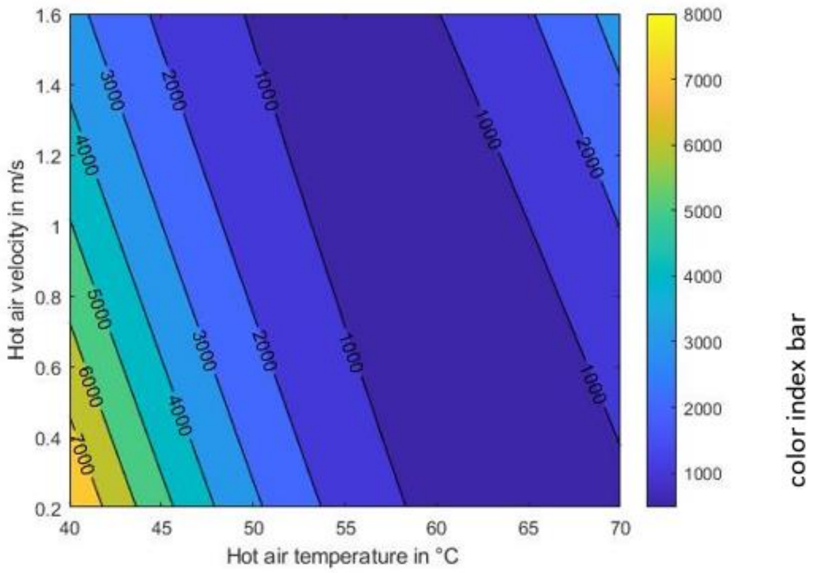

Figure 4.20 - Drying time versus hot air temperature and velocity

The drying time decreases as the hot temperature increases. When increasing the hot air velocity drying time reduces up to the temperature about 65 °C and beyond this limit again drying time increases.

4.5 Total Drying Energy

The total drying energy is estimated using the Equation 2.29.

$$E_{Total} = E_{thermal} + E_{mechanical}$$

Where, E_{Total} is the total drying energy, $E_{thermal}$ is the total thermal energy and, $E_{mechanical}$ is the total mechanical energy as shown in Equation 2.30.

$$\boldsymbol{E_{thermal}} = \mathrm{A.V.\rho.C.(t - t_{amb}).T}$$

The total drying energy required to dry 1 kg of raw black pepper was calculated and the results obtained are shown in Table 4.41

Table 4.41 - Total drying energy required for the different temperatures and air velocities

Temperature (^{0}C)	Hot air velocity (ms^{-1})	Drying Energy MJ
60	0.4	30.57
60	0.8	46.89
60	1.2	67.12
55	0.4	40.16
55	0.8	71.11
55	1.2	94.25
50	0.4	87.35
50	0.8	111.57
50	1.2	114.93

The fluctuation of total drying energy with heated air temperature and velocity is shown in Figures 4.21 and 4.22.

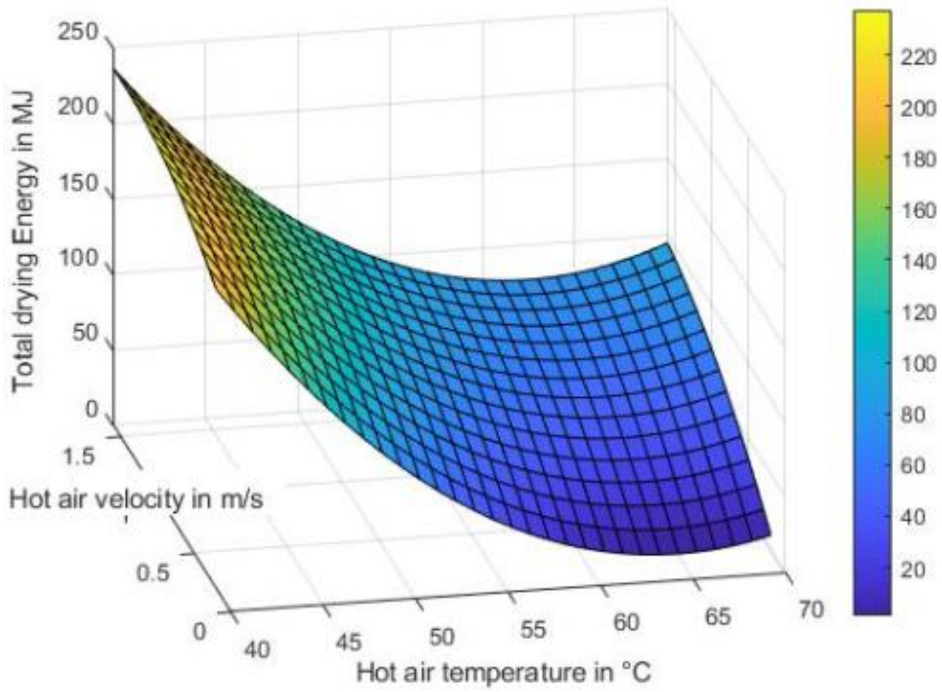

Figure 4.21 **-** The variation of total drying energy with hot air temperature and velocity

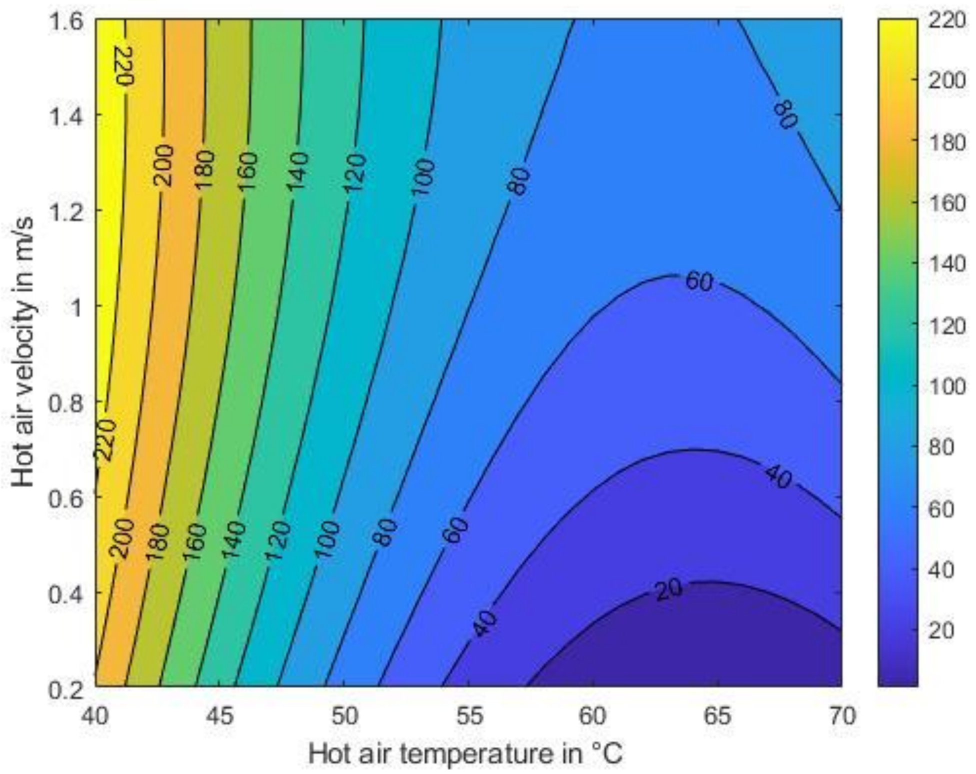

Figure 4.22 - Drying energy versus temperature and air velocity

The total drying energy versus hot air temperature for different hot air velocities are represented in Figure 4.16.

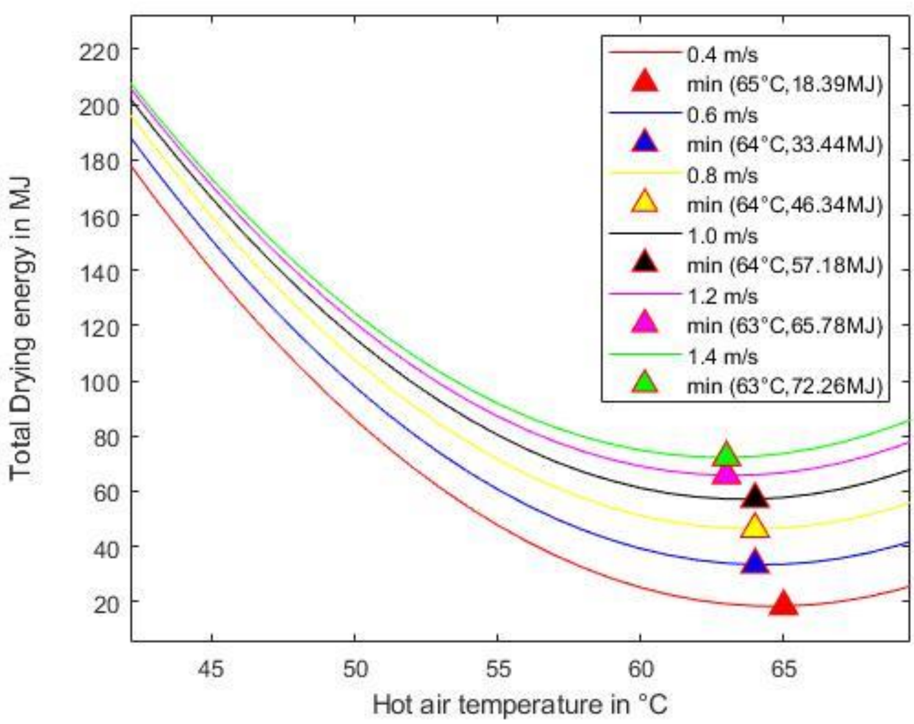

Figure 4.23 - The variation of total drying energy with hot air temperature for different hot air velocities

The total drying energy considerably reduces when increasing the drying temperature. Increase in temperature results to decrease the water viscosity and increase in kinetic energy of water molecules. That causes to enhance the capillary flow of water inside the food material and causes to increase in moisture diffusivity. Finally, it results to reduce the drying energy [7]. According to Figure 9, beyond a certain temperature limit drying energy increase that results due to limiting the heat transfer rate from hot air to the food being dried. Beyond that limit, most of the supplied energy is wasted and as a result drying energy increase.

4.6 Effective moisture diffusivity (D_{eff}) calculation

Effective moisture diffusivity is the main parameter which governs the drying process. To calculate the effective moisture diffusivity, the gradient of the plot of **ln (MR)** against the time **t** is needed. The plot of **ln (MR)** against the time **t** is given in Figure 4.24- 4.26 for different hot air temperatures and velocities.

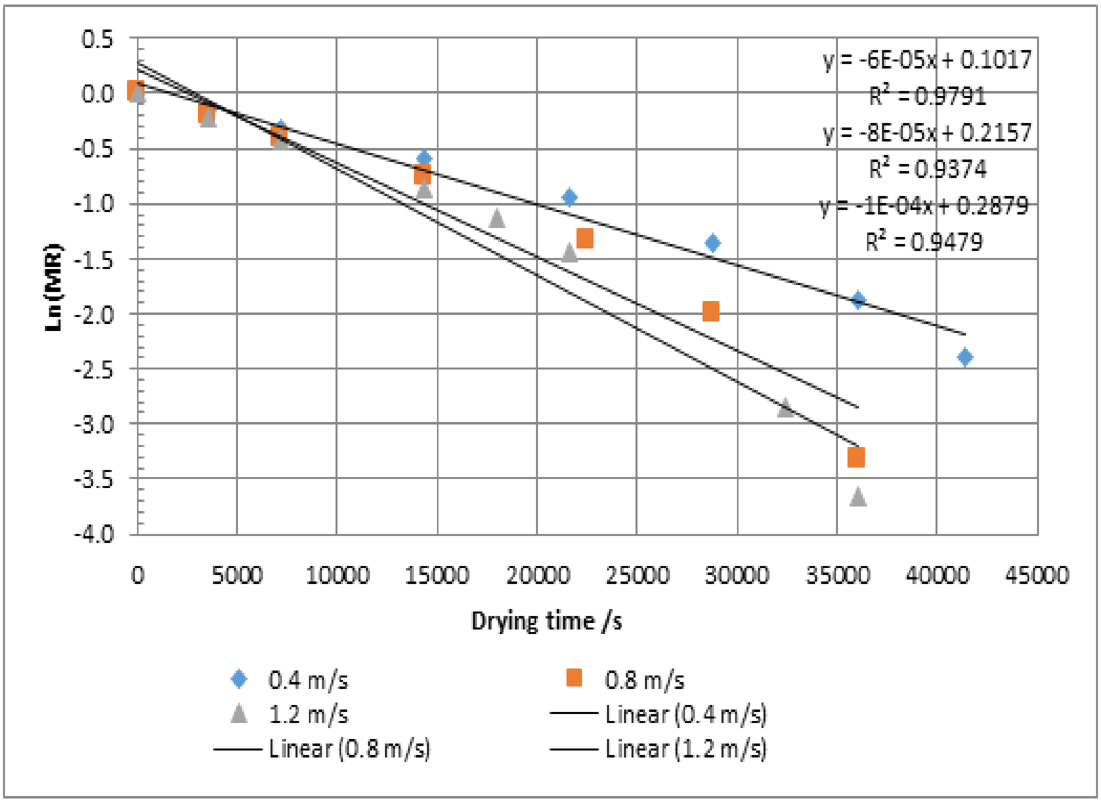

Figure 4.24 -The plot of ln(MR) against the time for drying under temperature of 60 °C

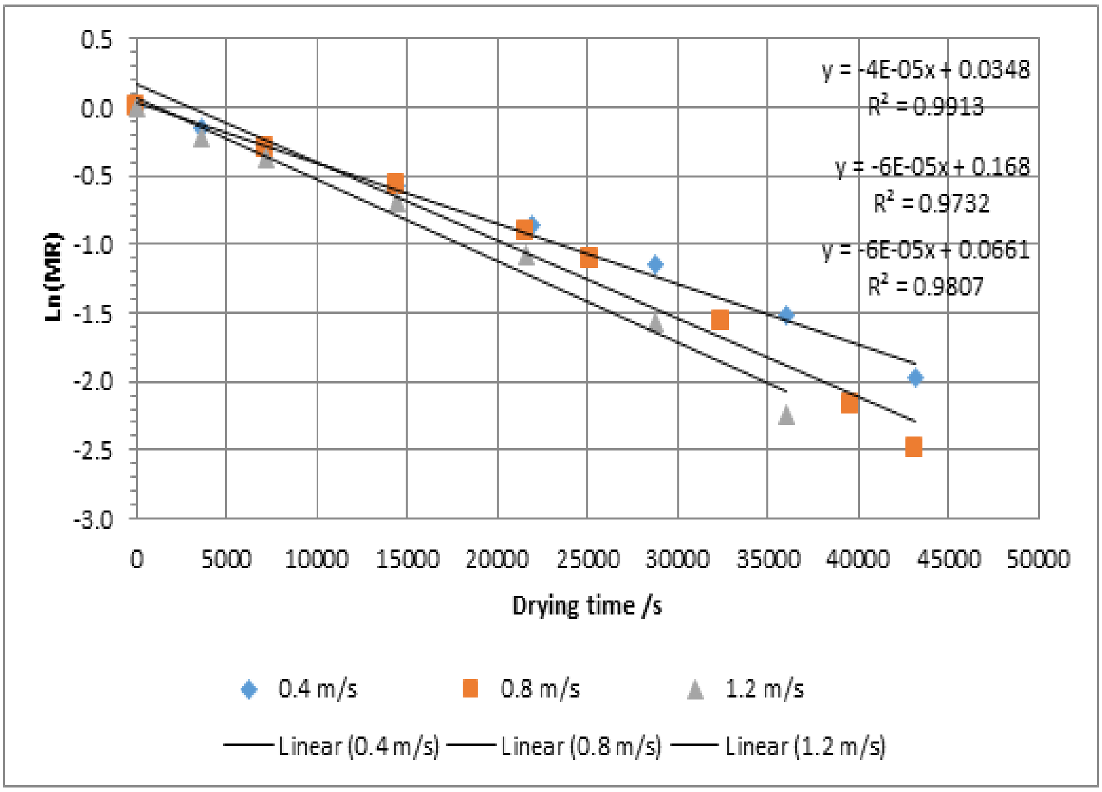

Figure 4.25 -The plot of ln(MR) against the time for drying under temperature of 55 °C

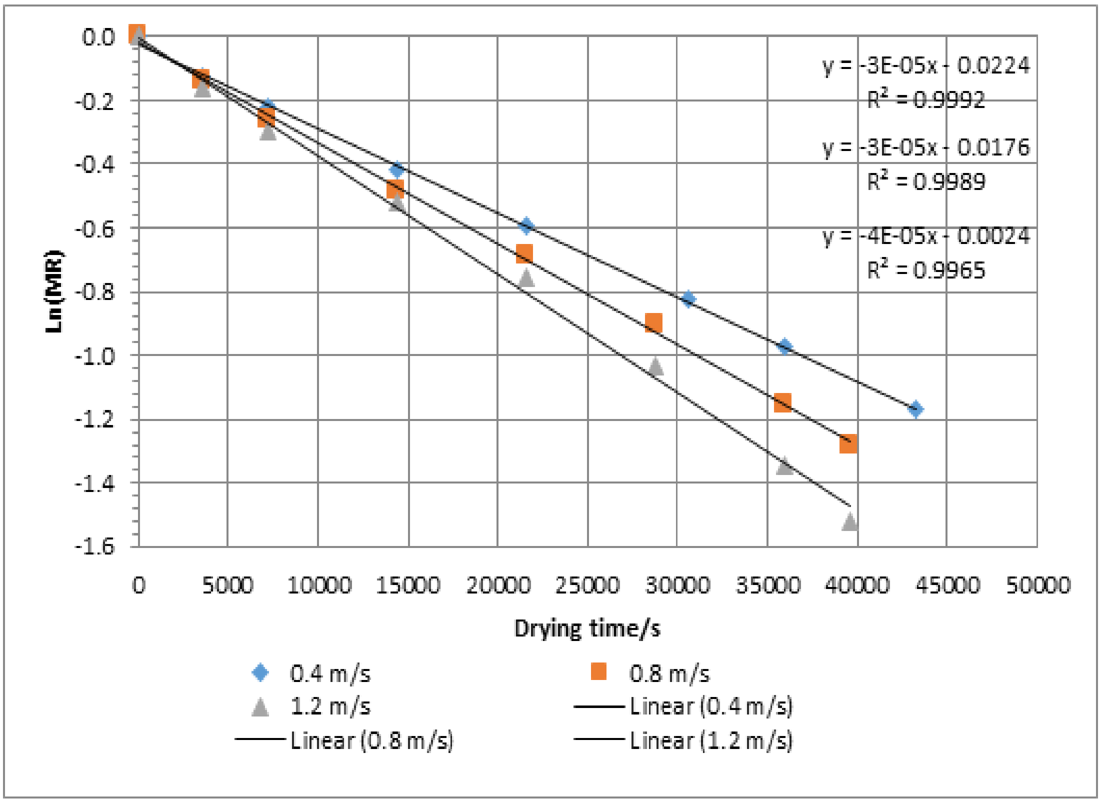

Figure 4.26 -The plot of ln(MR) against the time for drying under temperature of 50 °C

The effective moisture diffusivity was calculated using Equation 2.24 based on the gradient of the above plots.

$$D_{eff} = \left(-\frac{4R^2}{\pi^2}\right) \times Gradient$$

The calculated effective moisture diffusivity values are given in the Table 4.42

Table 4.42 - The gradient of the plot and the effective moisture diffusivity.

Temperature in ^{0}C	Hot air velocity in ms^{-1}	Gradient of the plot	Effective moisture diffusivity (D_{eff})
60	0.4	-0.000055	3.22E-10
	0.8	-0.000085	4.97E-10
	1.2	-0.000097	5.68E-10
55	0.4	-0.000044	2.58E-10
	0.8	-0.000057	3.34E-10
	1.2	-0.000059	3.45E-10
50	0.4	-0.000026	1.52E-10
	0.8	-0.000032	1.87E-10
	1.2	-0.000037	2.17E-10

The effective moisture diffusivity values obtained are of the same order of magnitude as the values obtained from available literature for black pepper drying. The Effective moisture diffusivity increases when increasing the drying temperature and hot air velocity.

4.7 Activation energy (E_0) calculation

The activation energy is a measurement of the minimum amount of energy required to initiate the drying process [21]. The activation energy can be computed using equation 2.27 by plotting ln(Deff) versus 1/(T+273.15). The plot of ln(D_{eff}) against the 1/(T+273.15) is given in Figure 4.27.

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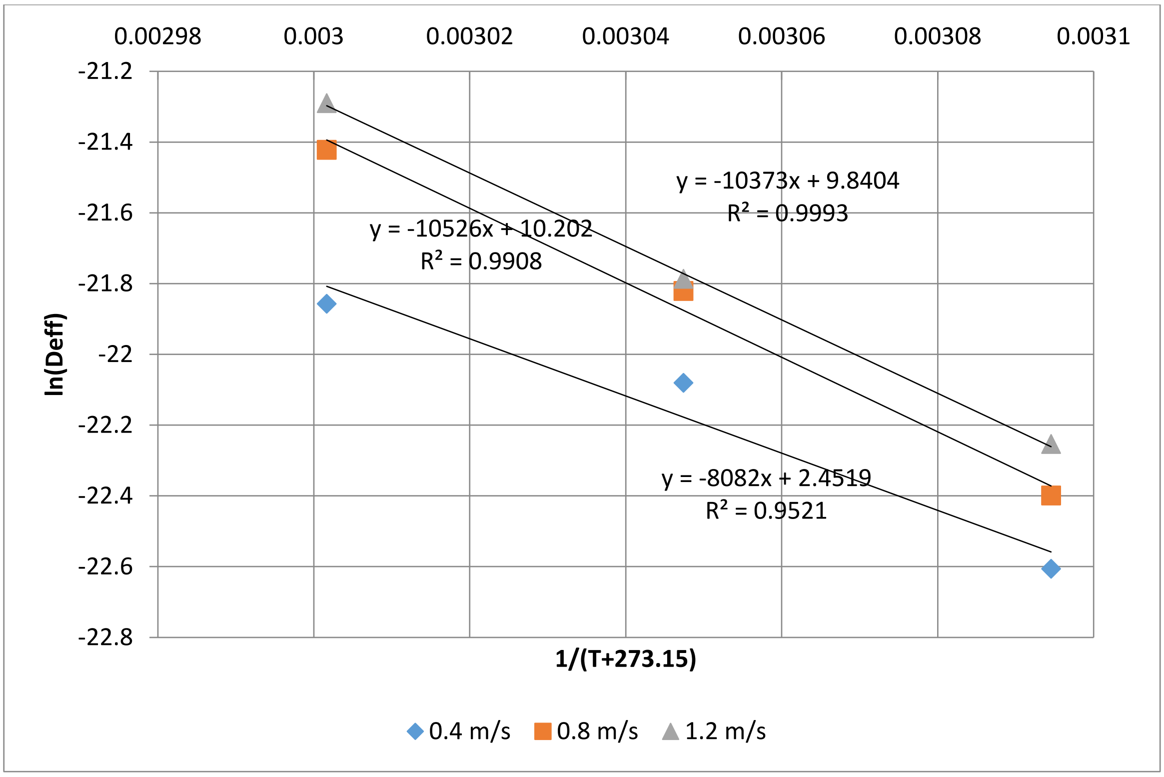

Figure 4.27 –The plot of ln(D_{eff}) versus 1/ (T+273.15)

Table 4.43 shows the activation energy values computed from the preceding analysis, and the activation energy increases with drying air velocity. The obtained values were in the same order of magnitude as the values obtained by other researchers for black pepper.

Table 4.43 - Activation energy for different drying air velocities

Air Velocity	Activation Energy / $kJ.mol^{-1}$
0.4 m/s	67.194
0.8 m/s	87.513
1.2 m/s	86.241

CHAPTER 5

5.0 CONCLUSIONS

The direct method was applied to determine the MC of raw black pepper, which was found to be 64.8 percent on a wet basis. Drying experiments were conducted for three different temperatures of 50 °C, 55 °C, and 60 °C, as well as three different air velocities of 0.4 ms-1, 0.8 ms-1, and 1.2 ms-1, to investigate the drying kinetics of black pepper dying on cabinet type tray dryers. Existing popular DMs were used to fit the observed experimental data. With an average RMSE of 0.01400, the logarithmic model was determined to be the best model for describing the drying behavior of black pepper in cabinet type tray dryer. The total drying time was calculated using the logarithmic DM for various temperatures and air velocities. The total drying energy was calculated using the found drying time, temperature, and air velocity. The total drying energy significantly varies with the drying air temperature and hot air velocity. It was observed that there is an optimum drying temperature around 65 °C for each hot air velocity which minimizes the total drying energy. Finally, it is concluded that a significant amount of energy can be saved by selecting the optimum operating condition for a dryer.

The effective moisture diffusivity values obtained ranged from $5.677E^{-10}$ - $1.522E^{-10}$ m^2s^{-1}. When the drying temperature and hot air velocity are increased, the effective moisture diffusivity increases. The Activation energy of black pepper was determined using the Arrhenius equation and obtained values were in the range 67.194 - 86.241 $kJ.mol^{-1}$. The activation energy values, and the effective moisture diffusivity values were in the same order of magnitude as the values obtained by other researchers for black pepper.

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