MATHEMATICAL MODELING OF DRYING KINETICS OF *GUNDRUK*

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by

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Mathematical Modeling of Drying Kinetics of *Gundruk*

A dissertation submitted to the Department of Food Technology, Central Campus of Technology, Tribhuvan University, in partial fulfillment of the requirements for the degree of B. Tech. in Food Technology.

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Approval Letter

This *dissertation* entitled *Mathematical Modeling of Drying Kinetics of Gundruk* presented by Prajwal Pokharel has been accepted as the partial fulfillment of the requirement for the B. Tech. degree in Food Technology

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Prajwal Pokharel

Abstract

Gundruk prepared from Rayo saag (*Brassica juncea)* was dried at was dried at 50, 55 and 60^0C air temperatures in cabinet drying and under Solar and Sun drying for modeling purpose. Moisture ratio of *gundruk* during drying was calculated and the data obtained tests were applied to 5 well-known semi-theoretical and empirical mathematical models of drying. Model constants and coefficients were determined by nonlinear regression method. All the models were validated using statistical parameters namely; R^2, RMSE, χ^2 and SSE.

Experimental result showed drying of *gundruk* falls in falling rate period. The rate of drying continuously decreased as drying proceeds. Graphical and statistical analysis of result showed that, Midilli model was best-fitted model for cabinet drying and logarithm was best-fitted for solar drying at both day-1 and midilli for day-2 with the higher value of value of R^2, and lower values of RMSE, χ^2 and SSE. The value of effective moisture diffusivity found is lowest for sun drying i.e. 1.0233×10^{-9} m^2/s and is highest for cabinet drying at 60^0C i.e. 9.1708×10^{-9} m^2/s. This shows that effective moisture diffusivity value increases with increase in drying temperature. The activation energy, which is an indicator of minimum energy required to remove moisture from a solid matrix was found to be 67.737 kJ/mol and the diffusivity constant D_o was found to be 391.075 m^2/s.

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List of Abbreviations

Abbreviation	Full forms
a, b, c	Drying rate constant obtained from experimental data
ASAE	American association of Agricultural Engineers
db	Dry basis
D_0	Arrheius factor
E_a	Activation energy
k,g,h	Drying rate constant obtained from experimental data
K_{11}, K_{22}, K_{33}	Phenomenological Luikov's Coefficients
K_{12}, K_{13}, K_{21}, K_{23}, K_{31}, K_{32}	Luikov's coupling coefficients
M_{db}	Dry basis moisture content
M_e	Equilibrium moisture content
MR	Moisture ratio
$MR_{exp,i,}$	i^{th} experimental MR
$MR_{pre,i}$	i^{th} Predicted MR
M_0	Initial moisture content
M_t	Moisture at time t
M_{wb}	Wet basis moisture content
n	Empirical model constant
N	Number of observation
R	Universal gas constant
RMSE	Root Mean Square Error
SSE	Sum of squared errors
t	Time
Wb	wet basis
W_d	Dried product Weight
W_0	Initial Weight

Part I

Introduction

1.1 General introduction

Gundruk is one of the most popular foods of Nepal. The word '*gundruk*' is derived from the Newari word 'gundru' (the Newaris being one of the ethnic groups of the Nepalese). Nepalese traditionally use it. The fermenting substrate for gundruk is usually 'rayo' (*Brassica campestris* L var *cumifolia* Roxb) leaves. Other leaves such as radish (*Raphanus sativus* L) shimarayo (*Cardamine hirsute* L var *sylvatica* Link), cauliflower (*Brassica oleracea* L var *botrytis* L), etc. are also used. *Gundruk* is usually prepared during the months of December to February when the weather is less humid and there is an ample supply of vegetables. Prepared in other seasons, particularly during the monsoon ,it is said to decay rapidly and to have an unpleasant flavor (Rao *et al.*, 2005).

The preparation takes about week to a month. Leaves are dried in the sun (1-2 days depending on the weather). The dried leaves, after mild crushing, are soaked briefly in hot water and hand-pressed in a perforated tin or earthen jar with a heavy article such as a large stone to remove surplus water. They are then kept in warm and dry place for fermentation. In village process, a hole of diameter and depth of ~1 m is dug in the ground and dried by fire. And a 30-cm layer of banana or bamboo leaves is placed in the bottom; the dried crushed leaves of the vegetables to be fermented are placed above this layer and covered with a further layer of banana or bamboo leaves. Heavy stones are added to compress the substrate. The holes are sometimes finally covered with a layer of cow dung. The leaves are allowed to ferment in situ until a fermentation odor develops. The *gundruk* is taken out and sun dried for 2-4 days. It has shelf life of about one year (Rao *et al.*, 2005).

A mathematical model is a simplified version of the word that is used to study key characteristics of that word. They are the representation of particular condition or idea. A model embodies a hypothesis about the study system, and lets you compare that hypothesis with data. Modeling is not perfect and usually is a simplification of reality (Amidror and Hersch, 2010). Mathematical modeling and simulation of drying curves under different conditions is important to obtain a better control of unit operation and an overall improvement of the final product. Models often used to study the variables involved in the process, predict drying kinetics of the product and to optimize the operating parameters and conditions (Meisami-asl *et al.*, 2009) . Drying modeling is generally carried out by using thin layer models, which are semi theoretical models, based on Fick's law of diffusion. Drying or Dehydration is not only energy intensive process but also an important unit operation that determines the product final quality. Since it is very critical process, it must be closely controlled in order to get higher quality product with minimum cost and this is possible only if we formulate the whole drying process. The thin layer drying modeling helps us to formulate drying process as well as dryer (Dandamrongrak *et al.*, 2002).

1.2 Statement of problem

Removing water from food and agricultural products constitutes a significant portion of the processing activity for persons working in the food and agricultural processing industries (Wilhelm *et al.*, 2004). Drying also exert great effect on the quality of dehydrated food. Drying simply refers to the removal of water from the tissue structure of food product. The physical, chemical, bio-chemical and microbiological changes which determine nutritional stability are closely connected with the status of water in food product. Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously, which is not easily understandable. The theoretical models may explain heat and mass transfer but it encounters unnecessary computational complexity and time commitment as well as less interpretable (Sahin and Dincer, 2005).

The drying modeling of *gundruk* has not been carried out till date. Because of which the technology of drying is still primitive. From engineering point of view, the drying process as well as drying parameters plays an important role in *gundruk* drying and the quality and acceptability of final dried product. The drying rate is strongly dependent on air velocity, temperature and relative humidity inside dryer. In order to achieve *gundruk* of better quality and for better process control, effect of these processing parameter on drying process must be identified. Moreover, the drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior and for optimizing the drying parameters (Hossain and Bala, 2002).

1.3 Objectives

1.3.1 General objective

The general objective of the study was mathematical modeling of drying kinetics of *gundruk.*

1.3.2 Specific objectives

To fulfill the general objective, specific objectives undertaken were as follows:

a) To prepare *gundruk* by using *Brassica juncea.*
b) To carry out drying at three different temperatures (50, 55 and 60°C) on a convective hot air cabinet dryer.
c) To fit the experimental drying curves to different drying models.
d) To carry out solar drying of *gundruk* and fit the data to different drying models.
e) To determine the effective moisture diffusivity and activation energy for diffusion during drying.
f) To determine the diffusivity constant (D_0).

1.4 Significance of the study

Mathematical modeling provides the basis for dehydration process of *gundruk* and gives suitable process formulation. The best process formulation helps us to reduce nutrient loss and enhance nutrient retention during product processing. It also gives suitable idea about the effect of variable in dehydration process (which is itself a preservation technique). The models developed have been used in calculations involving the design and construction of new drying systems, optimization of the drying process, and the description of the entire drying behavior of *gundruk* including heat and mass transfer. Thus, it is important to understand the basic idea of modeling the drying kinetics of food. The drying conditions, type of dryer, and the characteristics of the material to be dried all have an influence on drying kinetics. The drying kinetics models are therefore significant in deciding the ideal drying conditions, which are important parameters in terms of equipment design, optimization, and quality improvement of *gundruk.*

The modeling is basically based on the design of a set of equations to describe the system as accurately as possible. The most important aspects of thin-layer drying technology are the mathematical modeling of the drying process and the equipment design which can enable the selection of the most suitable operating conditions. Thus, there is a need to explore the thin-layer modeling approach as an essential tool in estimating the drying kinetics from the experimental data, describing the drying behavior, improving the drying process, and eventually minimizing the total energy requirement (Giri and Prasad, 2007). It represents the direct moisture product relationship to manage drying system. Also dryers can be designed especially for *gundruk* drying which brings us a step closer to industrial production of *gundruk.*

1.5 Limitations

a) Air velocity, RH and their effect during the course of drying were not studied and controlled.

b) Solar drying was done from 10 A.M to 4 P.M only.

Part II

Literature review

2.1 History of *gundruk* making in Nepal

From time immemorial, *gundruk* has been made in the country. Whether in village or in big cities, *gundruk* is relished by most Nepalese. *Gundruk* preparation is widespread in Nepal. This is basically because the traditional technology is rather straight forward, it does not demand extra requirements and raw materials are easily available (Upadhaya, 2002).

Gundruk is also a kind of preserved vegetable by fermentation. *Gundruk* is obtained from the fermentation of leafy vegetables and is indigenous to Nepal. It is served as a side dish with the main meal and is also used as an appetizer. *Gundruk* is also an important source of minerals particularly during the off-season when the diet consists of mostly starchy tubers and maize which tend to be low in minerals. *Gundruk* is a non-salted fermented acidic vegetable product indigenous to Nepal, commonly prepared during winter when perishable leafy vegetables are plenty. The most common raw material used for the preparation of *gundruk* in the country is mustard leaves. However, depending on the availability of the raw materials, *gundruk* has been prepared in the country using various other leaves, e.g. radish (*Raphanus sativus*), rapeseed (*Brassica campestris* var. *toria*), cauliflower (*Brassica oleracea*) etc. (Upadhaya, 2002).

Pediococcus and *Lactobacillus* species are the predominant micro-organisms during *Gundruk* fermentation. The fermentation is initiated by *L. cellobiosus* and *L. plantarum*, and other *homolactics* make a vigorous growth from the third day onwards. *Pediococcus pentosaceus* increases in number on the fifth day and thereafter declines (Shrestha *et al.*, 2012). During fermentation, the pH drops slowly to a final value of 4.0 and the amount of acid (as lactic) increases to about 1% on the sixth day. Nowadays indigenous foods are declining from the diet. The use of *gundruk* as food in Nepal is lost in antiquity but the popularity of the product is very high (Shrestha *et al.*, 2012).

The quality attributes to *gundruk*, basically depends upon the typical *gundruk* flavor and acidic taste. In a natural fermentation, the vegetable is acidfied by acid-forming bacteria that are capable of fermenting sugar present in the vegetable. The acidic taste is the measuring index of *gundruk* quality. In natural fermentation, the level of acidity varies thus some lots are better than the rest. Because of these characteristics, emphasis has been placed on the isolation of lactic acid bacteria that probably play the key role in *Gundruk* fermentation (Karki *et al.*, 1983).

2.2 Chemical Composition of mustard *gundruk*

The chemical composition of mustard *gundruk* are shown in Table 2.1

Table 2.1 Chemical composition of mustard *gundruk*

Parameter	Value per 100 g dry edible
Calories (cal)	19-30
Protein (%)	3.5
Fat (%)	0.1
Carbohydrate	1-2
Riboflavin (mg)	0.2
Niacin (mg)	0.5
Thiamine (mg)	0.07
Ascorbic acid (mg)	55.0

Source: Kharel *et al.* (2007)

2.3 Changes during *gundruk* fermentation

2.3.1 Chemical changes

The predominant chemical change in case of *gundruk* fermentation is conversion of sugar to organic acids, particularly lactic and acetic. In *gundruk* fermentation, sugar present in leaves is converted into lactic, acetic and other minor acids and small amounts of alcohols. On the basis of the end products formed, *gundruk* fermentation may be a homo- or hetero-fermentation. The LAB involved, by analogy, are designated as homo lactic (homo fermentative) and hetero lactic (hetero fermentative). The homolactics produce mainly lactic acid via Embden-Meyerhoff scheme of glycolysis and mainly involve Streptococcus, *Pediococcus* and various Lactobacillus species. The heterolactics consist of Lactobacillus and *Leuconostoc* species. They produce acetic acid, ethanol, carbon-dioxide, etc., in addition to lactic acid. For lactic acid fermentation, heterolactics are preferred since the end products (acetaldehyde and diacetyl) are responsible for the flavor of the product.

However, both homolactic and heterolactic fermentations have important practical implications.

During the course of fermentation, acidity increases by many folds. The final product contains about 0.5% acidity as lactic. The quality of *gundruk* mainly depends on the balanced production of lactic acid (about 50%) and acetic acid (about 35%). Organic acids not only contribute to the desired taste and flavor of the final product but also make the substrate unfavorable for proliferation of spoilage and other undesirable microorganisms. At the same time the acid makes the substrate more suitable for the growth of microorganisms that improve the properties of the food. The combined effect of these acids along with various other metabolites, CO_2 and ethyl alcohol contributes to the characteristics flavor and texture of *gundruk* (Kharel *et al.*, 2007). Shrestha (2002) observed crude protein, fat, crude fiber and ash content as 33%, 2.1%, 57.68%, and 0.68% respectively.

2.3.2 Changes in amino acids, lipids and flavors

Various changes in amino acids occur during *gundruk* fermentation. The extent of changes in all the 20 amino acids varies with the type of vegetable used for fermentation. Glutamate, alanine, and leucine increase more whereas threonine, glycine, cystein, methionine, isoleucine, phenylalanine and lysine increase less during fermentation. Asparagine, glutamine, proline, tyrosine, histidine and arginine decrease but aspartate, valine and tryptophan remain almost constant during fermentation (Kharel *et al.*, 2007).

The polar lipids constitute the major lipid component (Karki *et al.*, 1983). Other important lipid components are mainly comprised of free fatty acids, triglycerides, diglycerides, hydrocarbons, and unknown fractions. The most pertinent alteration of lipids during *gundruk* fermentation is the substantial increase in free fatty acids fraction. The glycerides and some unknown fractions are hydrolyzed during *gundruk* fermentation, liberating free fatty acids fraction that may be eventually beneficial for generation desirable ester-like flavor in *gundruk* (Upadhaya, 2002).

The main flavor component of mustard vegetable *gundruk* comprises of cyanides (15.7%), isothiocyanates (8.5%), followed by alcohols (12.5%) and esters (4.1%) (Upadhaya, 2002).

2.4 Drying

2.4.1 Introduction

Drying involves the application of heat to vaporize the volatile substances (moisture) and some means of removing water vapor after its separation from the solid (Jayaraman and Gupta, 1995). The drying process is a heat and mass transfer phenomenon where water migrates from the interior of the drying product on to the surface from which it evaporates. Heat is transferred from the surrounding air to the surface of the product. A part of this heat is transferred to the interior of the product, causing a rise in temperature and formation of water vapor, and the remaining amount is utilized in evaporation of the moisture from the surface (Lopez *et al.,* 2009).

Dehydration is the oldest method of food preservation practiced by man. For thousands of year man has dried and/or smoked meat, fish, fruits and vegetables, to sustain him during out of season periods in the year. Today the dehydration section of the food industry is large and extends to all countries of the globe. Drying facilities range from simple sun or hot air driers to high capacity, sophisticated spray drying or freeze drying installations. A very large range of dehydrated foods is available and makes a significant contribution to the convenience food market. The terms dehydration and drying are used interchangeably to describe the removal of most of the water, normally present in a foodstuff, by evaporation or sublimation, as a result of the application of heat. The main reason for drying a food is to extend its shelf life beyond that of the fresh material, without the need for refrigerated transport and storage. This goal is achieved by reducing the available moisture, or water activity to a level which inhibits the growth and development of spoilage and pathogenic microorganisms, reducing the activity of enzymes and the rate at which undesirable chemical changes occur (Brennan, 2006).

2.4.2 General principles

Drying can be described as the process of thermally removing moisture to yield a solid product. Moisture can be found as bound or unbound in the solid. Moisture, which exerts a vapor pressure less than that of pure liquid, is called bound moisture while moisture in excess of bound moisture is called unbound moisture.

The most important thermodynamic process in food drying is heat and mass transfer. During hot-air drying, there is a simultaneous exchange of heat and mass between the food and the drying air (Maroulis *et al.*, 1995).

a) Heat transfer
    1. Convective heat (energy) transfer from the air to the food`s surface (external heat transfer).
    2. Conductive heat transfer within the food (internal heat transfer)

b) Mass transfer
    1. Moisture transport within the food toward its external surface (internal mass transfer).
    2. Evaporation and convective transfer of the vapour into the air (external mass transfer)

Since the physical structure of the drying solid is subject to change during drying, the mechanisms of moisture transfer may also change with elapsed time of drying (larbi, 2014). Energy transfer as heat from the surrounding environment to the wet solid can occur as a subsequence of convection, conduction, or radiation and in some case as a result of a combination of these effect, however convection is common and predominant mechanism (Aguilera and Stanley, 1999; Heldman and Hartel, 1997). In most cases heat is transferred to the surface of the wet solid and then to the interior. This heat transfer to the food surface increases the sample temperature and supplies the required latent heat of vaporization for both the surface water and the water within the product. At the same time, internal moisture (mass) migrates to the surface of the food and then it evaporates to the surrounding hot air (Aversa *et al.*, 2007; Ramaswamy and Marcotte, 2006).

Transport phenomena involve both external and internal resistance to heat and/or mass transfer. The factors that slow the rate of these processes determine the drying rate (Ramaswamy and Marcotte, 2006; Singh and Heldman, 2009). In other words, the resistance mechanisms control the drying rate. In general, it is accepted that the rate of the drying may be limited either by the rate of internal migration of water molecules to the surface or by the rate of evaporation of water molecules from the surface into the air, depending on the conditions of drying (Singh and Heldman, 2009). This indicates that the resistance to mass transfer is considered to be the primary rate-limiting mechanism and the resistance to heat transfer may hence be neglected. The reason for this is that within the food, heat is usually transported more easily than moisture and thus the temperature gradients inside the food can be assumed to be flat (no resistance to internal heat transfer), especially when compared to the steep moisture content gradient (Fortes and Okos, 1981). In addition, it is known that heat transfer within the food may be limited by the thermal conductivity of the product as its water evaporates (Donsi *et al.*, 1996).

The air temperature, air humidity and velocity, and exposed surface area all influence the resistance to external heat and mass transfer whereas the internal mass transfer is only affected by the physical nature of the food, its moisture content and temperature. At the beginning of drying, since the internal resistance in the food is low enough to maintain the surface at saturation, evaporation takes place at a constant rate depending mainly on external heat and mass transfer. When the drying rate starts to decrease due to insufficient water at the surface, resistance to internal mass transfer governs the process. Most foods therefore switch from an external drying process during the initial stages to an internal drying process as the product dries out (Ramaswamy and Marcotte, 2006).

In addition, the drying rate in the food sample, which decreases from the very beginning of the process (at a constant temperature), may also indicate that the internal resistance to mass transfer controls the drying (Uddin *et al.*, 1990; Yusheng and Poulsen, 1988).

2.4.3 Drying mechanism

The movement of moisture during drying is shown in Fig. 2.1

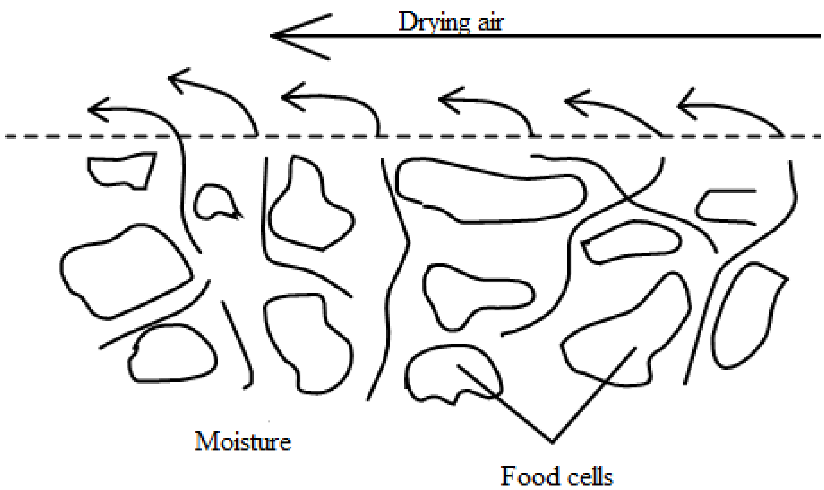

Fig. 2.1 Movement of moisture during drying

When hot air is blown over a wet food, heat is transferred to the surface, and latent heat of vaporization causes water to evaporate. Water vapour diffuses through a boundary film of air and is carried away by the moving air. This creates a region of lower water vapour pressure at the surface of the food, and a water vapour pressure is established from the moist interior of the food to the dry air. This gradient provides the driving force for water removal from the food.

Water moves to the surface by the following mechanisms:

a) Liquid movement by capillary forces
b) Diffusion of liquids, caused by differences in the concentration of solutes in different regions of the food
c) Diffusion of liquid which is adsorbed in layers at the surface of solid components of the food, and
d) Water vapour diffusion in air spaces within the food caused by vapour pressure gradients.

For a given food, the total amount of moisture that can be lost will vary with the humidity and temperature of the air. As water migrates out during drying, dissolved solids (sugar, acid, salt) are carried along to the surface. Here water evaporates into the air leaving the soluble solids which concentrate and may even precipitate at the surface. As the drying proceeds, the water removal may be restrained by the drying process itself. Food tissue often sinks as it loses moisture and the structure may change and blocks the exit of water. Such a condition is known as case hardening in which the outer trough surface is formed but still moist interior remains. The hard outer surface is more impermeable to water and such a product is susceptible to microbial spoilage. Less intense drying and intermittent conditioning alleviate this problem (kharel, 2006).

2.4.4 Factors affecting drying

According to Mujumdar (2006), the rate of drying is principally depend on internal and external condition.

a) External condition

The essential external variables are temperature, humidity, velocity and direction of air, the physical form of the solid, the desirability of agitation, and the method of supporting the solid during the drying operation. External drying conditions are especially important during the initial stages of drying when unbound surface moisture is removed. In certain cases, for example, in materials like ceramics and timber in which considerable shrinkage occurs, excessive surface evaporation after the initial free moisture has been removed sets up high moisture gradients from the interior to the surface. This is liable to cause over drying and excessive shrinkage and consequently high tension within the material, resulting in cracking and warping. In these case surface evaporation should be retarded through the employment of high air relative humidity while maintaining the highest safe rate of internal moisture movement by heat transfer.

Surface evaporation is controlled by the diffusion of vapor from the surface of the solid to the surrounding atmosphere through a thin film of air in contact with the surface.

b) Internal conditions

As a result of heat transfer to a wet solid, a temperature gradient develops within the solid while moisture evaporation occurs from the surface. This produces a migration of moisture from within the solid to the surface, which occurs through one or more mechanisms, namely, diffusion, capillary flow, internal pressures set up by shrinkage during drying. An appreciation of this internal movement of moisture is important when it is the controlling factor, as it occurs after the critical moisture content, in a drying operation carried to low final moisture contents. Variables such as air velocity and temperature, which normally enhance the rate of surface evaporation, are of decreasing importance except to promote the heat transfer rates. Longer residence times, and, where permissible, higher temperatures become necessary. The temperature gradient set up in the solid will also create a vapor–pressure gradient, which will in turn result in moisture vapor diffusion to the surface; this will occur simultaneously with liquid moisture movement.

2.4.5 The Drying curve

The drying curves are shown in Fig. 2.2 and 2.3.

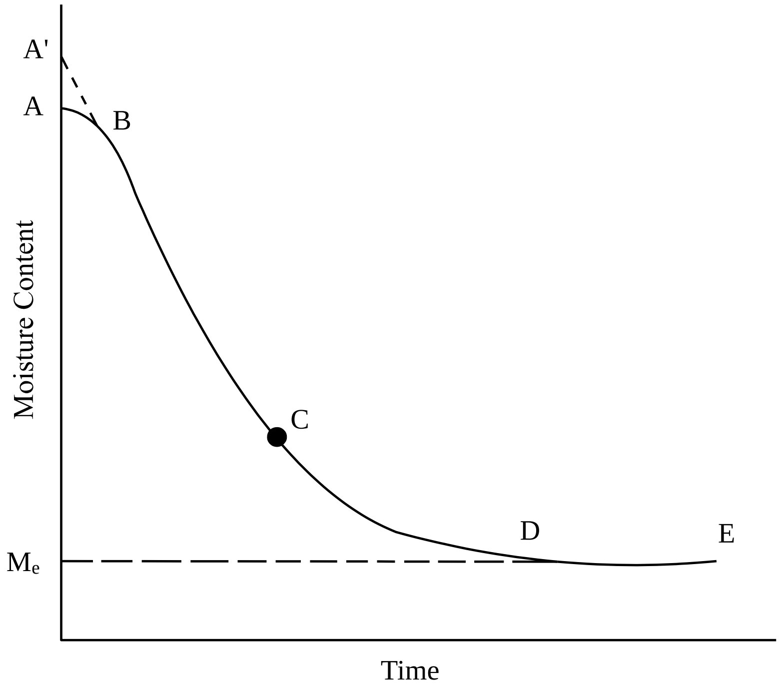

Fig. 2.2 Drying curve showing moisture content as function of time

Source: Geankoplis (2003)

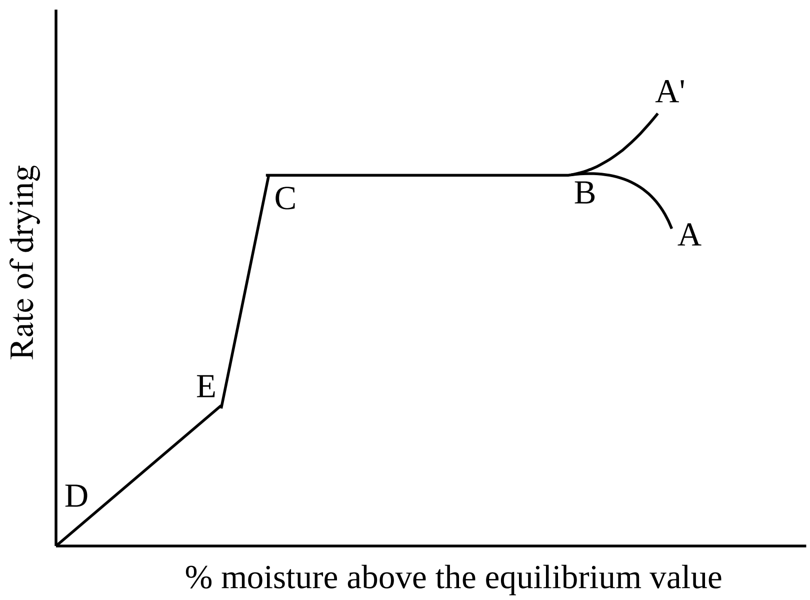

Fig. 2.3 Drying Rate as a Function of Moisture Content

Source: Geankoplis (2003)

Drying curve is the description of the changes of moisture content of material during drying. It can also be expressed as a drying kinetics or drying rate curve. It has also been reported by Prabhanjan *et al.* (1995) that the higher drying temperatures provide a larger water vapor pressure deficit or the difference between the saturated water vapor pressure and partial pressure of water vapor in air at a given temperature, which is one of the driving forces for drying.

Drying curve can be obtained experimentally by plotting the free moisture content versus drying time. This plot can be converted into a drying rate curve by calculating the derivative of the curve over time. From these two types of curve it is seen that drying is divided into two distinct portions. The first is the constant rate period (line BC) and second portion is falling rate period (line CE). Although the curve possesses two distinct phases, it contains total 3 stages. Pabis (1999), who presented an alternative approach to the convection drying of the products with high initial moisture content, such as vegetables and mushrooms, found the former approach flawed and argues that nonlinearity of changes in water content that occur during the initial period of convection drying of these products cannot justify the claim that the first period of drying does not exist.

I. Transition phase (A/A'-B)

It represents the setting down period during which the solid surface conditions come into equilibrium with the drying air. The point A and A' (Fig. 2.3) represent the initial conditions for a cold and hot material, respectively. It is often negligible proportion of the overall drying cycle but in some cases, may be significant

II. Constant Rate period (B-C)

During this period mostly unbound water is removed. Water evaporates as if there is no solid present, and its rate of evaporation is not dependent on the material being dried. The rate of moisture migration from the interior to the surface of the food is equals to the evaporation rate at the surface (i.e. there is no internal resistance to mass transfer). In this stage of drying the rate-controlling step is the diffusion of the water vapor across the air-moisture interface. This period continues until water from the interior is no longer available at the surface of food material. The rate of heat transfer from the air to the food surface, on the other hand, is balanced by the rate of energy removal due to the evaporating moisture (i.e. latent heat of vaporization). Thus, the surface temperature remains at some constant value, which is in fact lower than air temperature due to the cooling effect of the evaporating water on the surface. Finally, water evaporates into the drying air as a result of the water concentration gradient and/or water vapour pressure gradient between the surface of the food and the drying air, and remains the same throughout the constant drying period (Heldman and Hartel, 1997; Ramaswamy and Marcotte, 2006).

III. Falling rate period (C-E)

Point C distinguishes the constant rate period from the subsequent falling rate period and is called the critical moisture content. As the free and loosely bound moisture contents in the product diminish and mass transfer from the surface to the drying air becomes smaller, the internal resistance to moisture transfer begins to drive the drying process. This is represented in Fig. 2.3 at the end of the second stage where the drying rate is no longer constant but falls progressively throughout the rest of the drying. The drying period beyond this point is termed as the falling-rate period, the surface of the solid is no longer wet (Fellows, 2000).

It may be divided into different sub-periods depending on the structure of the dried material e.g. hygroscopic and non-hygroscopic. In the case of non-hygroscopic materials there is a single falling rate period, while hygroscopic ones may exhibit two or more falling rate periods. This is explained by the fact that a non-hygroscopic material (e.g. sand, polymer particles and some ceramics) exerts the same partial water vapour pressure, at all moisture contents due to the negligible amount of physio-chemically bound water and the non-shrinkage property of such material. This partial water vapor pressure is equal to saturated water vapor pressure. In the case of a hygroscopic material, however, partial water vapor pressure is dependent on the moisture content due to the large amount of physio-chemically bound water and the occurrence of shrinkage during drying (Lewis, 2014).

The first falling rate period, the third phase (C-D) (Fig. 2.3), follows the end of equilibrium at the surface, which occurs when there is insufficient supply of water from the inner parts of the food. This results in the appearance of increasingly larger proportions of dry spots on the surface, leading to the reduction of surface area for evaporation and an increase in surface temperature (Heldman and Hartel, 1997). The second falling-rate period (D-E), the fourth phase, begins when the surface is completely dry, but the changeover between the periods is not always clear-cut. For example, in some cases no sharp discontinuity occurs at the end of the first falling-rate period due to the gradual change from partially wetted to completely dry conditions at the surface. During the second falling-rate period, the plane of evaporation slowly recedes from the surface and all evaporation occurs at the interior of the food. Therefore, changes in the external conditions such as air velocity and humidity no longer affect the rate of drying (Geankoplis, 2003).

In addition, the latent heat of vaporization of water at this stage of the drying process is higher than the latent heat of vaporization of pure water since water in the food sample is held in multiple layers (i.e. bound water). As a result, the amount of water removed is relatively small, while the time required is long. This causes the most heat damage to the food and therefore during this period the air temperature should be controlled to balance the rate of drying and extent of heat damage (Geankoplis, 2003).

The drying rate in the falling rate period is controlled by diffusion of moisture from the inside to the surface and then mass transfer from the surface. During this stage some of the moisture bound by sorption is being removed. As the moisture concentration is lowered by drying, the rate of internal movement of moisture decreases. The rate of drying falls even more rapidly than before and continues to drop until the moisture content falls down to the equilibrium value for the prevailing air humidity and then drying stops. Equilibrium between the material and the drying air is reached as the food temperature approaches the drying air temperature. At this point, the partial water vapour pressure of the food and the drying air become equal. The air fails to pick up any moisture from the product and thus drying ceases. The moisture content at this stage is the level to which food can be dried under a given drying condition and is referred to as the equilibrium moisture content (Heldman and Hartel, 1997).

2.5 Intermittent drying

Intermittent drying is a non-continuous drying process with tempering periods. It involves strict control of the heat input (drying temperature) such that the food material is subjected to particular air conditions at different points over the course of drying. Heat is supplied intermittently rather than continuously throughout the drying process. That is, the drying cycle, which consists of a drying and a tempering period, is repeated until the moisture content of the food product is reduced to the desired level (Xing *et al.*, 2007).

Drying causes moisture gradients to develop within the food products, which in turn decrease the drying rate. Tempering periods allow for moisture diffusion from the interior to the external surface of the food sample, thus decreasing such moisture gradients. This happens when the sample surface and the pores close to the surface are saturated with water that has been transferred from the inner sections. The resultant uniform distribution of moisture contributes to a reduction in drying time in the oven, thus reducing the total cost of the drying process. Indeed, after tempering, the surface moisture is easily removed in subsequent drying periods in the oven, which improves the drying rate. This phenomenon is referred to in the literature as the "refreshing effect" (Nishiyama *et al.*, 2006).

The length of tempering periods used in intermittent drying varies widely. It is important to know the tempering time that is appropriate for a particular set of conditions. The tempering time should be as short as possible to minimize the damage to the food sample caused by chemical changes, respiration and microbial activity. The duration and frequency of tempering depend on the time intervals of both the drying phase and the tempering phase and are greatly affected by the drying temperature. Higher temperatures shorten the required tempering times. Consequently, the total drying time necessary for reaching the desired moisture content (<15% wb) depends on the lengths of both the drying period and the tempering period (Cihan and Ece, 2001a).

Rate of moisture removal continuously decrease with increase in time (Boiln and Salunkhe, 1982).Two drying curves are obtained because of stop of drying at night. During night slight decreased in moisture content occur due to internal heat which is accumulated by product during day and also moisture redistributed within the product and hence increased in moisture occur at the surface of product (Karaaslan *et al.*, 2016)

2.6 Drying methods

2.6.1 Traditional sun drying

The traditional method of drying, known as 'sun drying', involves simply laying the product in the sun on mats, roofs or drying floors. Because the energy requirements - sun and wind - are readily available in the ambient environment, little capital is required. Sun drying of fruits and vegetables is still practiced largely.

During sun drying heat is transferred by convection from surrounding air by absorption of direct and diffuse radiation on the surface of crop. The converted heat is partially used to increase the temperature of food product and part of heat is used in effective moisture diffusion from interior to surface. The remaining amount of energy is used for the evaporation of water from the surface. The evaporated water has to be removed from surrounding of the crop by natural convection supported by wind forces (Bux *et al.*, 2002).

Sun drying has the advantages of simplicity, capital and operating costs and the fact that little expertise is required. On the other hand, there are many technical problems which are uncertainties like rain and cloudiness, contamination from outer sources and lack of control over drying conditions. It requires large areas and long drying time. The final product may have relatively high moisture content; low and variable quality of products due to over- or under-drying, product may contaminate from dust and insects, birds and suffer from enzyme and microbial activity. It is limited to climates with hot sun and dry atmosphere with strong winds (Jayaraman and Gupta 2006).

2.6.2 Solar drying

Solar dryers have some advantages over sun drying when correctly designed. They give faster drying rates by heating the air to 10-30°C above ambient, which causes the air to move faster through the dryer, reduces its humidity and deters insects. The faster drying reduces the risk of spoilage, improves quality of the product and gives a higher throughput, so reducing the drying area that is needed. However, care is needed when drying fruits to prevent too rapid drying, which will prevent complete drying and would result in case hardening and subsequent mold growth. Solar dryers also protect foods form dust, insects, birds and animals. They can be constructed from locally available materials at a relatively low capital cost and there are no fuel costs. Thus, they can be useful in areas where fuel or electricity are expensive, land for sun drying is in short supply or expensive, sunshine is plentiful but the air humidity is high. Moreover, they may be useful as a means of heating air for artificial dryers to reduce fuel costs (Fellows,1997).

The principle that lies behind the design of solar dryers is as follows: in drying relative and absolute humidity are of great importance. Air can take up moisture, but only up to a limit. This limit is the absolute (maximum) humidity, and it is temperature dependent. When air passes over a moist food it will take up moisture until it is virtually fully saturated, that is until absolute humidity has been reached. But, the capacity of the air for taking up this moisture is dependent on its temperature. Higher the temperature, the higher will be the absolute humidity, and the larger the uptake of moisture. If air is warmed, the amount of moisture in it remains the same, but the relative humidity falls; and the air is therefore enabled to take up more moisture from its surrounding (Gavhale *et al.*, 2015).

2.6.3 Cabinet drying

The majority of industrial drying installations rely on convectional hot-air drying at atmospheric pressure since it is the simplest and most economical among the various methods. A wide variety of food materials such as fruit, vegetables, herbs and cereal crops has therefore been dried by convectional hot-air dryers. In addition, it is easy to set and control the optimum drying conditions in these dryers, especially in cabinet dryers. Common atmospheric hot-air dryers include kiln, cabinet (tray), tunnel, and belt or conveyor dryers (Jayaraman and Gupta, 1995; Us and Khan, 2007).

The basic configuration of an atmospheric hot-air dryer is an enclosed and heated chamber where food material is placed. It is also equipped with a blower (i.e. fan) and ducts to allow the circulation of hot air around and across the food. When there is no fan the drying takes place under natural convection. The drying process in an atmospheric dryer involves both heating the product and removing water from the product surface (Rahman and Perera, 1999).

Traditional convective drying methods employ continuous constant air temperature for moisture removal from the food product. The transfer of thermal energy from the heater to the food substance occurs by means of convection. The penetration of this thermal energy is dependent on the thermal conductivity of the material. During drying, as moisture leaves the pores in the outer layers of the food, it is replaced by gas (air). This results in a decrease in the thermal conductivity of the outer layers since the thermal conductivity of air is lower than that of water. Consequently, the product surface behaves like an insulator. The penetration of the delivered heat to the inner section of the food sample is reduced progressively, and water is transferred more slowly to the surface, where evaporation occurs. Thus high heat transfer rates applied at the surface will only result in overheating or over-drying of the surface layer leading to quality problems without a significant increase in the drying kinetics (Lewis, 1987).

2.6.4 Some terminologies

2.6.4.1 Equilibrium moisture content

The term "EMC" is an acronym for equilibrium moisture content. The term is used in relation to a hygroscopic material. The term hygroscopic refers to a material that absorbs or bleeds moisture from or into the atmosphere. Equilibrium moisture content is defined as the point where stops absorbing moisture from or bleeding moisture into the surrounding air. At this point, the material is said to have reached equilibrium with the atmosphere (Heldman and Hartel, 1997).

2.6.4.2 Critical moisture content

At certain moisture content, dry regions begin to exist on the surface, and the drying rate begins to decrease. This moisture level is called the critical moisture content. In other word it is the moisture content at which constant rate of drying disappear and falling rate starts. Here the surface of the solid is no longer wet. The critical moisture content depends on the thickness of the bed of material and the degree of mixing between the gas and solids. The critical moisture content is therefore not a property of the material itself and must be determined experimentally (Geankoplis, 2003).

2.6.4.3 Moisture content

The quantity of moisture present in a material can be expressed either on the wet basis or dry basis and expressed either as decimal or percentage. The moisture content on the wet basis is the weight of moisture present in a product per unit weight of the undried material, represented as,

$$MR = \frac{W_o - W_d}{W_o}$$

Where,

M_{db} = moisture content at wet basis

W_o = initial weight

W_d =final weight after drying

While the moisture content on the dry basis (M_{db}) is the weight of moisture present in the product per unit weight of dry matter in the product and represented as,

$$MR = \frac{W_o - W_d}{W_d}$$

The moisture content on the wet basis is used normally for commercial purposes, while the moisture content on the dry basis has tended to be employed for engineering research designation. Because the weight change associated with each percentage point of moisture reduction on the dry basis is constant as against the wet basis where the amount of water involved in a moisture content reduction of one percent changes as drying progresses, because the weight of water and total crop weight change.

2.4.6.4 Moisture ratio

Moisture ratio is one of the important criteria to determine the drying characteristics of agricultural product. MR can be determined according to external conditions. If the relative humidity of the drying air is constant during the drying process, then the moisture equilibrium is constant too. In this respect, MR is determined as in Eq.

$$MR = \frac{M_t - M_e}{M_o - M_e}$$

Where,

MR = moisture ratio

M_t = moisture content at any time (t)

M_o = initial moisture content

M_e = equilibrium moisture content

If the relative humidity of the drying air continuously fluctuates, then the moisture equilibrium continuously varies, MR is determined as given by Diamante and Munro (2006).

$$MR = \frac{M_t}{M_o}$$

2.4.6.5 Drying rate

Agricultural products differ from most other materials dried frequently, such as textiles in a Laundry, sand, stone, dust or paper. Agricultural products (which are hygroscopic) has always some residual moisture after the drying while for non-hygroscopic material drying continued up to zero moisture content. Because of hygroscopic products moisture is trapped in closed capillaries. The rate of moisture flow is only approximately proportional to its vapor pressure difference with the environment because of the crop resistance to moisture flow. There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period;

$$\text{Drying rate} = \frac{M_{t+dt} - M_t}{dt}$$

2.7 Mathematical modeling of agricultural products

Mathematical modeling is the process of constructing mathematical objects whose behaviors or properties correspond in some way to a particular real-world system. In this description, a mathematical object could be a system of equations, a stochastic process, a geometric or algebraic structure, an algorithm, or even just a set of numbers. The model should be usable for predicting either future behavior or behavior under different circumstances, or for better understanding the situation (Malkevitch *et al.*).

Mathematical modeling and simulation of the drying curve direct better control of drying and to obtain high quality product. The researchers prefer to model the convection drying of vegetables, fruit, and grass by using differential equations of internal mass diffusion or semi-empirical exponential equations developed to account for the second period of drying of grain (Demir *et al.*, 2004).

Mathematical modeling is generally done for following reason:

1. To gain understanding

Generally speaking, if we have a mathematical model which accurately reflects some behavior of a real-world system of interest, we can often gain improved understanding of that system through analysis of the model. Furthermore, in the process of building the model we find-out which factors are most important in the system, and how different parts of the system are related.

2. To predict or simulate

Very often we wish to know what a real-world system will do in the future, but it is expensive, impractical, or impossible to experiment directly with the system (Umlis and Othmer, 2014)

Different types of Mathematical models have been used in order to explain different behavior and characteristic of agricultural products, such as Drying, Rehydration, sorption isotherm, fermentation etc. Here, drying characteristic of product has been studied by different thin layer drying equations.

2.8 Thin Layer Drying

According to ASAE (2005), thin layer drying refers to a layer of material exposed fully to an airstream during drying. There is a wide range of thin layer drying models, thin layer drying models which have found application because of their ease of use. Thin layer drying equations are often empirical to describe drying phenomena in a unified manner regardless of the controlling mechanism. Thin layer drying equations are used to estimate the drying time of several products and also to generalize drying curves (Kadam *et al.*, 2011).

Drying is one of the most complex and least understood processes at the microscopic level, because of the difficulties and deficiencies in mathematical descriptions. It involves simultaneous and often coupled and multiphase, heat, mass, and momentum transfer phenomena (Yilbas *et al.*, 2003). In addition, the drying of food materials is further complicated by the fact that physical, chemical, and biochemical transformations may occur during drying, some of which may be desirable. Physical changes such as glass transitions or crystallization during drying can result in changes in the mechanisms of mass transfer and rates of heat transfer within the material, often in an unpredictable manner (Mujumdar, 1997).

The underlying chemistry and physics of food drying are highly complicated, so in practice, a dryer is considerably more complex than a device that merely removes moisture, and effective models are necessary for process design, optimization, energy integration, and control. Although many research studies have been done about mathematical modeling of drying, undoubtedly, the observed progress has limited empiricism to a large extent and there is no theoretical model that is practical and can unify the calculations (Maroulis *et al.*, 1995).

The term “thin layer” has been applied to:

- A single material freely exposed to the drying air or one layer of the material
- A polylayer of many materials slice thicknesses if the temperature and the relative humidity of the drying air can be considered for the purpose of the drying process calculations, as being in the same thermodynamic state at any time of drying.

It means that, the thickness of a thin layer can increase if the velocity of the drying air increases and also if the thermodynamic state of the drying air approaches the equilibrium state in heat and mass transfer with grain dried in this layer (Onwude *et al.*, 2016). According to Chakraverty (1994), layer thickness upto 20 cm can be consider as thin layer.

Thin layer drying equations are important tools in mathematical modeling of drying. They are practical and give sufficiently good results. To use thin layer drying equations, the drying-rate curves have to be known.

2.9 Thin Layer Drying mechanism

The main mechanisms of drying are surface diffusion on the pore surfaces, liquid or vapour diffusion due to moisture concentration differences and capillary action in granular and porous foods due to surface forces (Erbay and Icier, 2010b). Generally, hygroscopic products dry in constant rate and subsequent falling rate periods and drying stops when equilibrium is established (Erbay and Icier, 2010b). During the constant rate period of drying, the physical form of the product and external conditions such as temperature, drying air velocity, direction of air flow and relative humidity have a great influence on the surface of the product being dried so called surface diffusion. Unlike the constant rate periods, the falling rate period is controlled by liquid diffusion as a result of moisture concentration differences and the internal conditions of the product. The internal conditions such as moisture content, the temperature and the structure of the product play an important role in the falling rate periods.

2.10 Mathematical models of Thin Layer Drying

Thin layer drying equation is fundamental to the drying simulation. The equation represents moisture exchange between a thin layer of the drying product with its surrounding air. From a mathematical point of view, a thin layer represents the spatial dx that is chosen infinitesimal small within which changes in humidity and temperature of the air can be assumed linear (Wang *et al.*, 2004).

2.10.1 Theoretical models

The theoretical models consider both the external and internal resistance to moisture transfer. They involve the geometry of the material, its mass diffusivity, and the conductivity of the material (Cihan and Ece, 2001b).

It is further sub divided into two groups,

2.10.1.1 Distributed model

Distributed models consider simultaneous heat and mass transfer. This model or system is based on the interaction between time and one or more spatial variables for all of its dependent variables. They take into consideration both the internal and external heat and mass transfer, and predict the temperature and the moisture gradient in the product better.

Generally, these models depend on the Luikov equations that come from Fick`s second law of diffusion shown as below or their modified forms Luikov (1975).

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} T$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} T$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32} T + \nabla^2 K_{33} T$$

Where, K_{11}, K_{22}, K_{33} are the phenomenological coefficients, while K_{12}, K_{13}, K_{21}, K_{23}, K_{31}, K_{32} are the coupling coefficients, M is the local moisture content on a dry basis, T is temperature and P is partial pressure. For most of the processes, the pressure effect can be neglected compared with the temperature and the moisture effect, so the Luikov equations become as,

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T \quad \text{.........................Eq. (1)}$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T \quad \text{............................ Eq. (2)}$$

Nevertheless, the modified form of the Luikov equations may not be solved with analytical methods, because of the difficulties and complexities of real drying mechanisms.

2.10.1.2 Lumped parameter models

Lumped parameter models do not pay attention to the temperature gradient in the product and they assume a uniform temperature distribution that equals to the drying air temperature in the product. This model or system considers the effect of time alone on the dependent variables with this assumption, the modified Luikov equation further becomes,

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \quad \text{.. Eq. (3)}$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M \quad \text{.. Eq. (4)}$$

Phenomenological coefficient K_{11} is known as effective moisture diffusivity (D_{eff}) and K_{22} is known as thermal diffusivity (α). For constant values of D_{eff} and α these equations can be rearranged as:

$$\frac{\partial M}{\partial t} = D_{eff} \left[\frac{\partial^2 M}{\partial X^2} + \frac{a_1}{X} \frac{\partial M}{\partial X} \right] \quad \text{................................ Eq. (5)}$$

$$\frac{\partial T}{\partial t} = \alpha \left[\frac{\partial^2 T}{\partial X^2} + \frac{a_1}{X} \frac{\partial T}{\partial X} \right] \quad \text{.................................. Eq. (6)}$$

Where, parameter for planar geometries, a_1= 1 for cylindrical shapes and a_1= 2 for spherical shapes.

The resistance to moisture transfer in theoretical model involves the geometry of the material, its mass diffusivity, and the conductivity of the material (Cihan and Ece, 2001b).

Thus the resistances can be estimated from Eq. 3 and 4 because these equations describe the mass transfer (Erbay and Icier, 2010b). Equation 5 under some assumption and boundary condition can describe mass transfer with good degree of accuracy. Eq. 5 can be analytically solved with the assumptions, and the initial and boundary conditions, which are as follows;

- Assumptions

  - The particle is homogenous and isotropic;
  - The material characteristics are constant, and the shrinkage is neglected;
  - The pressure variations are neglected;
  - Evaporation occurs only at the surface;
  - Initially moisture distribution is uniform and symmetrical during process;
  - Surface diffusion is ended, so the moisture equilibrium arises on the surface;
  - Temperature distribution is uniform and equals to the ambient drying air temperature, namely the lumped system;
  - The heat transfer is done by conduction within the product, and by convection outside of the product;
  - Effective moisture diffusivity is constant versus moisture content during drying.

Then analytical solutions of Fick`s law are given below for infinite slab:

$$MR=\frac{M-M_e}{M_o-M_e}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{2n+1}\exp\left[\frac{-(2n+1)^2\,\pi^2 D_{eff}\,t}{4\left(h^*\right)^2}\right]$$

Where, D_{eff} is the effective moisture diffusivity in m^2/s, h^* is the half thickness of slab and n is the number of terms (as a positive integer).

However, in practice, for long drying period only first term of the series is often applied because the value of rest terms is negligible. Hence, the above equation is simplified to

$$\text{Ln(MR)} = \text{Ln}\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2} \times t$$

2.10.2 Semi-theoretical or Semi- empirical models

The semi-theoretical models are generally derived by simplifying general series solutions of Fick`s second law or modification of simplified models and are valid within the experimental temperature, relative humidity, air velocity and moisture content range (Panchariya *et al.*, 2002). Semi-theoretical models can also be derived from Newton`s law cooling. Here are some of the semi-theoretical models that are widely used in describing the thin layer drying characteristics of agricultural products (Erbay and Icier, 2010a).

Factors that could determine the application of these models include the drying temperature, drying air velocity, material thickness, initial moisture content, and relative humidity (Erbay and Icier, 2010a). Furthermore, under these conditions it can be noted that the complexity of the models can be attributed to the number of constants, i.e. greater the number of constraints more complex will be the model and hence it is difficult to understand the mechanism.

On the basis of products nature, it is further subdivided in to two groups;

2.10.2.1 Models derived from Newton’s law of cooling

A. Lewis Model

This model is analogous with Newton`s law of cooling so many investigators named this model as Newton`s model. Lewis described that the moisture transfer from agricultural materials can be seen as similar to the law of heat from a body immersed in cold fluid. First, Lewis (1921) suggested that during the drying of porous hygroscopic materials, the change of moisture content of material in the falling rate period is proportional to the instantaneous difference between the moisture content and the expected moisture content when it comes into equilibrium with drying air. So this concept assumed that the material is thin enough, or the air velocity is high, and the drying air conditions such as the temperature and the relative humidity are kept constant.

$$\frac{dM}{dt} = -K\left(M\text{-}M_e\right)$$

Where, K is the drying constant. In the thin layer drying concept, the drying constant is the combination of drying transport properties such as moisture diffusivity, thermal conductivity, interface heat, and mass coefficients (Maroulis *et al.,* 1995). Newton`s law of cooling assumes that, the internal resistance to moisture movement and thus moisture gradients within the material are negligible. It considers only the surface resistance (Madamba, 2003).

Assuming a boundary condition as M= M_o at t=0, the solution of the above equation can also be rewritten as;

$$MR= e^{-kt}$$

Where, k = drying constant and t = time

This is one of the simplest models describing moisture movement for food products. The most important drawback of this model is that, it generally underestimates late stages and overestimates early stages of the drying process (Hossain and Bala, 2002). This model has been widely and successfully used by some researchers to model the drying behavior of agricultural products such as strawberry, red chilli, grape seed and black tea.

B. Page model

The Page model or the Modified Lewis model is an empirical modification of the Newton model, whereby the errors associated with using the Newton model are greatly minimized by the addition of a dimensionless empirical constant (n). This parameter has an effect of moderating the time, and the model in this case gives better results for the prediction of moisture loss (Doymaz and Ismail, 2011).

$$MR= e^{-kt^n}$$

This model has 2 constants and is widely used as the basis for most semi-theoretical thin-layer models. This model has been used by many researchers to describe the rate of moisture loss during thin layer drying of agricultural materials under constant drying conditions. It was successfully used to describe the drying characteristics of some agricultural products such as banana, date palm, green bean, kiwifruit, mango, onion, bitter melon etc.

C. Modified Page model

As the name implies, this is a modification of the Page model. Erbay and Icier (2010a) reported 3 forms of the Modified Page model (I, II, and III). For the purpose of this literature review, the following Modified Page models (Eq. 7 and 8) have been found to be the most suitable in describing the drying behavior of different fruits and vegetables. They include,

$$MR = e^{(-kt)^n} \quad \ldots\ldots\ldots\ldots\ldots.. \text{ Eq. (7)}$$

Eq. (7) is widely regarded as the Modified Page model. This model has 2 constants and has been applied in predicting the drying kinetics of mint leaves and basil leaves.

$$MR = Ke^{\left(\frac{-t}{d^2}\right)^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{ Eq. (8)}$$

Where d is an empirical constant (dimensionless).

Eq. (8) can be called the Modified Page model (III). This model has 3 constants and can successfully describe the drying behavior of onion.

2.10.2.2 Models derived from Fick's second law of diffusion

A. Henderson and Pabis model

We already got the simplified form for Fick`s law of diffusion as,

$$Ln(MR) = \frac{M - M_e}{M_o - M_e} = Ln\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2} \times t$$

- Assumptions:

- The surface moisture content of the food material is in equilibrium with the temperature and relative humidity of the surrounding air,
- Temperature of food material is in equilibrium with drying air,
- The diffusion coefficient remains unchanged during the course of drying

Then above equation becomes;

$$MR= a e^{-kt^n}$$

Where a= $\frac{8}{\pi^2}$ and k= $\frac{\pi^2 D_{eff}}{4(h^*)^2}$

This can also be regarded as a simple model with only 2 model constants. The Henderson and Pabis (1961) model has been effectively applied in the drying of crops such as corn and millet. However, it has not been quite so successful in describing the drying behavior of fruits and vegetables, since the model has been found applicable only to apple. This model effectively predicts the drying rate at the beginning of the drying process, but appears sometimes to be less efficient for the last stages of the process (Dissa *et al.*, 2008). The slope of this model, “k”, is related to effective diffusivity when drying process takes place only in the falling rate period and liquid diffusion controls the process (Panchariya *et al.*, 2002) and a represents the shape of the materials used (dimensionless).

B. Modified Henderson and Pabis model

The modified Henderson and Pabis model is a third term general solution of the Fick`s second law of diffusion for correction of the shortcomings of the Henderson and Pabis model. It has been reported that the first term explains the last part of the drying process of food and agricultural products, which occurs largely in the falling late period, the second term describes the midway part, and the third term explains the initial moisture loss of the drying process (Erbay and Icier, 2010a). The model contains 6 constants and based on this, the model has been referred to as complex thin-layer model.

$$MR= ae^{-kt} + be^{-gt} + ce^{-ht}$$

where, a, b, and c are defined as the indication of shape and generally named as model constants (dimensionless), and k, g, and h are the drying constants (s^{-1}). These constants are obtained from experimental data.

This model does not effectively describe the drying process of most fruits and vegetables. This model has been found to only successfully describe the drying kinetics of pretreated pumpkin.

C. Logarithmic model

This model is also known as an asymptotic model and is another modified form of the Henderson and Pabis model. It is actually a logarithmic form of the Henderson and Pabis model with the addition of an empirical term. The model contains 3 constants and can be expressed as

$$MR = ae^{-kt} + c$$

Where, c is a dimensionless empirical constant. This model has been found to be the fourth best thin-layer model in describing the drying kinetics of various fruits and vegetables. Consequently, the model has produced the best fit in predicting the drying kinetics of apple, basil leaves, beetroot, pumpkin, and stone apple.

D. Two-term model

The 2-term model is a second term general solution of the Fick`s second law of diffusion. The model contains 2 dimensionless empirical constants and 2 model constants which can be derived from experimental data. The first term describes the last part of the drying process, while the second term describes the beginning of the drying process. For most fruits and vegetables with high moisture content, this model can well be suitable as it assumes a constant product temperature and diffusivity throughout the drying process. This model well describes the moisture transfer of the drying process, with the constants representing the physical properties of the drying process.

$$MR = ae^{-k_1 t} + be^{-k_2 t}$$

Where a and c are dimensional less constant and k_1 and k_2 are drying constants (s^{-1}). This model predicts the moisture transport well and its parameters represent the physical properties of the drying process. It is successfully applied to explain drying behavior of prickly pear fruit (Lahsasni *et al.*, 2004) and cladodes (López *et al.*, 2009) sultana grapes (Yaldiz *et al*., 2001), garlic (Sacilik and Unal, 2005) and pumpkin (Zenoozian *et al*., 2008).

E. Two-term exponential model

The 2-term exponential model is a modification of the 2-term model by reducing the number of constants and modifying the indication of shape constant (b) of the second exponential term. Erbay and Icier (2010) emphasized that constant "b" of the 2-term model has to be (1-a) at t =0 in order to obtain a moisture ratio of MR = 1. The model has 3 constants and can be expressed as,

$$MR = ae^{-kt} + \left(1-a\right)e^{-kat}$$

This model has been found successful in describing the drying kinetics of only star fruit.

F. Approximate diffusion model

The Approximate Diffusion model is another modification of the 2-term exponential model with the separation of the drying constant "k" and t with a new dimensionless constant "b" in the second part of the model.

$$MR = ae^{-kt} + \left(1-a\right)e^{-kbt}$$

Where, b is also a dimensionless model constant.

This model has been applied with great success in the determining the drying kinetics of green pepper, pumpkin, and tomato.

G. Verma *et al.* model

This model is another modification of the two-term model with 4 model constants. The Verma *et al*. (1985) model has been applied successfully in describing the drying kinetics of parsley and pumpkin.

$$MR = ae^{-kt} + \left(1-a\right)e^{-gt}$$

Where, g is also a drying constant (s^{-1})

H. Midilli model

Midilli *et al*. (2002) proposed a new model by a modification of the Henderson and Pabis model by the addition of an extra ‘t’ with a coefficient. The new model, which is a combination of an exponential term and a linear term, has been validated by testing the model on mushroom, pollen, and pistachio.

$$MR= ae^{-kt} + bt$$

Where, a and b are the model constants and k is the drying constant (s^{-1}) to be estimated from the experimental data. This model is sometimes called the Midilli Kucuk model or the Midilli model. It contains 3 constants and has been found to be the best in describing the drying behavior of different fruits and vegetables. It has been found to be suitable in describing the drying kinetics of fruits and vegetables such as apple, chili, golden apples, hawthorn, jackfruit, kiwifruit, mango, ginger, pepper, persimmon, pineapple, saffron, spearmint.

I. Modified midilli model

Midilli *et al.* model is composed of an exponential and a linear term describing the moisture ratio as a function of drying time;

$$MR=ae^{-kt^{n}} + bt$$

This model is also similar to Henderson and Pabis model with an addition of an empirical term to “t”. The Midilli *et al*. model was successfully used in studying the drying characteristics of agricultural products such as savory leaves celery leaves, various vegetables like pumpkin and also fruits like apple (Menges and Ertekin, 2006).

Midilli model has been found suitable in describing the drying kinetics of many fruits and vegetables. This model has found excellent in describing drying kinetics of apple slices corresponding to similar statistical result having the value of R^2, χ^2 and RMSE 0.9979, 1.7×10^{-4} and 0.01357 respectively (zarein *et al.*, 2013). Similarly, Midilli model has been found best fitted in in describing the drying behavior of various porous leaves such as celery leaves, spanich leaves (Simha and Gugalia, 2013). Mint leaves such as spear mint leaves (Ayadi *et al.*, 2014) and also has described the dying kinetics of saffron. This model has also found excellent in describing drying kinetics of various vegetables such as pumpkin and fruits such as jack fruit, kiwi fruit, golden apples (Menges and Ertekin, 2006), mango, ginger and spice like pepper (Onwude *et al.*, 2009).

J. Hii and other model (modified 2-term model)

The Hii *et al*. (2009) can also be referred to as a Modified Page model or, more appropriately, a Modified 2-term model. The model involves a combination of the Page and the 2-term model. The first part of the model is exactly as the Page model. However, it more theoretically describes the model as a modified 2-term model with the inclusion of a dimensionless empirical constant “n.” The model contains 5 constants and can be referred to as a complex model in this regard. Hii *et al.* (2009) proposed this model for the drying of cocoa beans. However, it has been found appropriate in describing the drying kinetics of some fruits,

$$MR = ae^{-k_1 t} + be^{-k_2 t}$$

The Hii and others model has been successfully applied to the drying of carrot pomace and pumpkin.

2.10.3 Empirical models

Empirical models give a direct relationship between the average moisture content and the drying time. The empirical models also have similar characteristics to semi-theoretical models. They strongly depend on the experimental conditions and give limited information about the drying behaviors of the product (Erbay and Icier, 2010a).

The empirical method is based on experimental data and dimensional analysis. They are easily applied to drying simulation, as they depend on experimental data. Empirical models consider only the external resistance to moisture transfer between the product and air. The major limitation to the application of empirical models in thin-layer drying is that they do not follow the theoretical fundamentals of drying processes in the form of a kinetic relationship between the rate constant and the moisture concentration, thus giving inaccurate parameter values. Moreover, these models do not have a physical interpretation and are wholly derived from experimental data (Onwude *et al.*, 2016).

The 3 most widely applied empirical models for the drying kinetics of fruits and vegetables as reported in the literature are:

A. Wang and Singh model

This model was developed for the intermittent drying of rough rice (Wang and Singh, 1978). The model gives a good fit to the experimental data. However, this model has no physical or theoretical interpretation, hence its limitation.

$$MR=1+at+bt^2$$

Where, a and b are dimensionless model constants gotten from the experimental data. This model has been found to successfully explain the drying behavior of banana.

B. The Thompson Model

The Thompson model is an empirical model obtained from experimental data by correlating the drying time as a function of the logarithm of the moisture ratio. The model cannot successfully describe the drying behavior of most fruits and vegetables because it has no theoretical basis and lacks physical interpretation. However, the model has been found to be suitable for describing the drying kinetics of green peas and blueberries. The model can be expressed as,

$$t = a + Ln(MR) + b + [Ln(MR)]^2$$

Where, a and b are dimensionless empirical constants.

C. Peleg Model

This model is generally used to model the Rehydration characteristic of food products but Peleg model gives good fit for drying of some biological product. It has been applied successfully only in describing the drying behavior of banana.

$$M= M_o + \left[\frac{1}{a+bt}\right]$$

Where, M = moisture content at time t (%), M_o = initial moisture content (%), a = peleg constant (h^{-1}), b = peleg capacity constant, t = hour

2.11 Effective Moisture Diffusivity

Diffusion in solids during drying is a complex process that may involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. With a lumped parameter model concept, all these phenomena are combined in one term named as effective moisture diffusivity (D_{eff}). The diffusion coefficient is defined as the volumetric flow rate of moisture transfer per unit area per unit thickness of grain. It is a rate term which does not directly include the driving potential which, in this case, is the moisture gradient (Brooker *et al.*, 1974; Henderson and Pabis, 1961).

D_{eff} mainly varies with internal conditions such as the products temperature, the moisture content, and the structure. The solution to the diffusion equation depends on whether the diffusion coefficient is considered to be a constant or a variable as well as on the boundary conditions considered. Diffusivity kinetic models are used to interpret the phenomenon of drying and thus the estimated values will be optimized by the model hypothesis such as boundary conditions, geometry, constant or variable physical and transport properties of isothermal and non-isothermal drying. The effective moisture diffusivity, which is a function of temperature and the moisture content of a material, is an important transport property in the modeling of the drying process of fruits and vegetables. Experimentally, effective moisture diffusivity is calculated by Fick`s second law of diffusion.

By applying assumption and boundary conditions Fick`s second law of diffusion is reduced to;

$$\text{Ln(MR)}= \text{Ln}\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}\times t \ \ldots\ldots\ldots\ldots\ldots\ (*)$$

by comparing the above equation to y= mx + c

$$\text{slope(m)}= \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$$

Above indicates that the variation of Ln(MR) values versus t is linear and the slope is equal to drying constant (k). By revealing the drying, the constant effective moisture diffusivity can be calculated easily with different geometries. By determining the slope of Ln(MR) vs. t graph, we can easily determine D_{eff} for that particular product.

As a matter of fact, the drying curves have a concave form when the curves of Ln(MR) vs t are analyzed. The concave form of drying curves is caused by variation of the moisture content and D_{eff} during drying. Because of this, the slopes have to be derived from linear regression of Ln(MR) vs t data. Experimental evidence shows that the diffusion coefficient increases with temperature of the drying air. The temperature dependence can be expressed by an Arrhenius type Equation (Akpinar *et al.*, 2003).

$$D_{eff} = D_o \exp\left(\frac{-E_a}{RT_a}\right)$$

Where, E_a - activation energy (KJ/mol)

R- Universal gas constant (8.3143×10^{-3} kJ $mol^{-1}K^{-1}$),

T_a - Absolute air temperature (K), and

D_0 - The pre-exponential factor of the Arrhenius equation (m^2/s).

It may be observed that Equation (*) does not take into account the continuously changing moisture content during drying. Further, it is based on the assumptions that temperature and the surface moisture content of grain are in equilibrium with the surrounding. Because of these simplifying assumptions, Equation (*) does not describe the drying data over the entire range for determining activation energy (Babalis and Belessiotis, 2004).

The values of effective diffusivities lie within the general range of i.e. 10^{-9} to 10^{-12} for drying of fruits and vegetables (Ankita and prasad, 2013). Similar results have been obtained for various leaves drying such as spanich , parsley leaves and mint leaves (Akpinar, 2006) A similar observation has been reported for increase in diffusivity coefficient as air drying temperature increases (Rahman and Kumar, 2007).

2.12 Statistical analysis for determination of appropriate models

In order to find best suitable model to explain drying behaviour of any product with different drying methods or different conditions, statistical methods are generally used. The main methods used for drying studies in the literatures are given below;

2.12.1 Coefficient of determination (R^2)

It is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It is the proportion of variability in a data set that is accounted for by the statistical model. It provides a measure of how well future outcomes are likely to be predicted by the model. The coefficient of determination is not likely to be 0 or 1, but rather somewhere in between these limits. The closer it is to 1, the greater relationship exists between experimental and predicted values (Neter *et al.*, 1990). This value is used for the quantitative comparison criteria and shows the level of agreement between measured and predicted values (Hossain and Bala, 2002). It is sometimes called as correlation coefficient (Akpinar, 2006; Gunhan *et al.*, 2005; Sobukola *et al.*, 2008) or determination coefficient (Vega-Galvez *et al.*, 2011). Although there are several different definitions of R^2 , it can be calculated by;

$$R^2 = \frac{\left(\sum M_{exp} \times M_{pre}\right)^2}{\sum M_{exp}{}^2 \times \sum M_{pre}{}^2}$$

2.12.2 Coefficient of correlation (r)

It is the square root of R^2 (Neter *et al.*, 2004). This is a measure of the correlation (linear dependence) between two variables, giving a value between +1 and −1 inclusive. It is widely used in the sciences as a measure of the strength of linear dependence between two variables. It is called as correlation coefficient (Magalhaes and Pinho, 2008; Erbay and Icier, 2009) or correlation index (Sander and Kardum, 2009) and given as;

$$r = \frac{N\sum_{i=1}^{N} MR_{pre,i} MR_{exp,i} - \sum_{i=1}^{N} MR_{pre,i} \sum_{i=1}^{N} MR_{exp,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR^2{}_{pre,i} - \left(\sum_{i=1}^{N} MR^2{}_{pre,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR^2{}_{exp,i} - \left(\sum_{i=1}^{N} MR_{exp,i}\right)^2\right)}}$$

2.12.3 Chi-square test (χ^2)

It is the mean square of the deviations between experimental and predicted values for the models and used to evaluate the fitting agreement of each model. Lower the values of χ^2, better the goodness of the fit (Yang *et al.*, 2007). It is called as mean squared deviation (Cihan *et al.*, 2007; Celen *et al.*, 2010), reduced mean square of deviation (Demir *et al.*, 2007), mean square of deviation (Jain and Pathare, 2004; Doymaz, 2004) and could be calculated as follows;

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n}$$

2.12.4 Root-mean-square error (RMSE)

It is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modeled or estimated. RMSE is a good measure of accuracy and serves to aggregate the residuals into a single measure of predictive power. It is required to reach zero and can be calculated as (Wang *et al.*, 2007)

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2\right)^2$$

It is called as root mean square analysis, standard deviation, root mean sum error, standard error, root mean square difference and root mean square deviation.

There is also another form of root mean square deviation (Contreras *et al.*, 2008)

$$\frac{1}{N}\sqrt{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}$$

2.12.5 Sum of squared errors of prediction (SSE)

In statistics, the sum of squared residuals (SSR) or the sum of squared errors of prediction (SSE) is the sum of the squares of residuals (deviations predicted from actual empirical values of data). It is a measure of the discrepancy between the data and an estimation model. A small SSE indicates a tight fit of the model to the data. It is used as an optimality criterion in parameter selection and model selection (Anon.).

$$\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2$$

2.13 Procedure for finding best-fit model

In order to select the most suitable model describing thin layer drying behavior and conditions for any specific application the following steps should be taken into consideration;

Calculate the values of correlation coefficient, the coefficient of determination, adjusted R^2 the reduced chi-square and the root mean square error. Determine and select the highest values of the correlation coefficient, the coefficient of determination, modeling efficiency, adjusted R^2. Determine and select the lowest values of the reduced chi-square and the root mean square error. Determine the drying curve model that has the highest values of the criteria i.e. R^2 and the lowest values of the criteria i.e. reduced chi-square, root mean square error and sum of square error. This model can be assumed to be best model describing the thin-layer drying curve.

2.14 Effective moisture diffusivity

The simplified form of Fick`s second law of diffusivity is given as;

$$\text{Ln(MR)} = \text{Ln}\,\frac{8}{\pi^2} - \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2} \times t$$

The diffusion coefficient is determined by plotting the experimental drying data in terms of Ln(MR) versus time. A plot of Ln(MR) versus time gives a straight line with a slope of;

$$\text{Slope(m)} = \frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$$

Part III

Materials and methods

3.1 Materials

3.1.1 Green leafy vegetable

Mustard green (*Brassica juncea)* was brought from local market of Dharan.

3.1.2 Fermentation container

Food grade, air tight, odorless and non-breakable plastic jar (500 ml) was used.

3.1.3 Equipment

The following equipments were used in this study

a) Dryer
   - Solar dryer: locally made solar dryer found in Central Campus of Technology, Hattisar was used.
   - Cabinet dryer (AISET YLD)

b) Digital thermometer

c) Electronic Balance (MRRS Digi Model MTT-T)

d) Hot Air Drying Oven

e) pH meter (labtronics,Panchkula,India)

3.2 Methods

3.2.1 Preparation of raw material for fermentation

Fresh Rayo saag (*Brassica juncea)* was bought from the market and preliminary treatments was done viz. cleaning, washing and removal of roots. Then it was wilted in sun for one day. After that it was crushed and soaked in warm water for 15 min (Tamang and Tamang, 2010).

3.2.2 Fermentation

About 400 g of crushed leaves were put into sterile 500 ml jar, pressed with sterile pestle to remove excess water. Then, bottles were tightly capped and fermented at room temperature (20–25°C) for the days until constant pH develops.

3.2.3 Flowchart for *gundruk* preparation

The flow chart for *gundruk* preparation is shown Fig. 3.1.

“Rayo-saag” (*Brassica juncea*)

↓

Wilting in the sun for 1 day

↓

Crushing

↓

Soaking in warm water.

↓

Putting into 500-ml Jar

(400g crushed leaves)

↓

Pressing with pestle

↓

Sealing the bottles tightly

↓

Fermentation (20-25℃)

Fig 3.1 Process of *gundruk* prepration

Source: Tamang and Tamang (2010)

3.3 Drying

3.3.1 Solar drying

Drying commenced from 10 a.m. till 4 p.m daily and was terminated when the moisture content reached less than 9% . Moisture content less than 10% is safe for *gundruk* in terms of long term storage. 100 g samples taken from different fermented jar and placed in tray. Samples were spread on the tray as a single layer (bed thickness of about 4 cm) and are weighed at every interval of 1h in the case of solar drying.

3.3.2 Cabinet drying

Gundruk was dried in Cabinet dryer continuously till the moisture content of product reached below 9.5% i.e. till the changes in weight between two successive readings becomes negligible. *Gundruk* was dried at 3 different temperatures i.e. 50, 55 and 60°C for several hours.

In cabinet dryer *gundruk* was dried. 100 g samples taken from different fermented jar and placed in tray. Samples were spread on the tray as a single layer (bed thickness of 4 cm) and are weighed at every intervals of 15 min in the case of cabinet drying.

3.4 Drying kinetics modeling

3.4.1 Drying kinetics modeling procedure

Fermented samples were dried by traditional solar dryer and cabinet drier found on Central Campus of Technology, Dharan laboratory. Air temperature was measured by Thermometer respectively.

a) The un-dried *gundruk* after fermentation was subjected to different drying mechanism.
b) After regular interval of drying (1 h for solar dried and 15 min for Cabinet dried sample) Changes in weight were noted until the change in weight was negligible.
c) Observed readings were converted to dry basis moisture content as,

$$MR = \frac{W_o - W_d}{W_o}$$

Observed dry basis moisture content was then converted to experimental Moisture ratio.

$$MR=\frac{M_t}{M_o}$$

d) The obtained data was fitted by using Microsoft excel (i.e. non-linear curve fitting) and then compared to standard curves.
e) A graph between experimental MR vs time was plotted.
f) The plotted experimental graph was then compared with standard curve of particular equation.
g) Then, Chi-square, corrected correlation coefficient, and root mean square error value was determined on the basis of experimental and predicted moisture ratio value.
h) Finally, the best curve was selected by evaluating Chi-square (χ^2) test, correlation coefficient, root mean square error (RMSE) and sum of square error (SSE).

3.4.2 Drying kinetics modeling equations

The experimental moisture ratio value was then compared with 5 most popular and widely acceptable thin layer modeling equations. These models were selected on the basis of more variables value, as drying doesn't depend on single factor. Different kinetics models used are tabulated in Table 3.1

Table 3.1 Different thin layer drying modeling equations

Models	Equations
Modified Henderson and pabis model	$MR= ae^{-kt}+be^{-gt}+ce^{-ht}$
Logarithm model	$MR= ae^{-kt}+c$
Two term model	$MR= ae^{-k_1t}+be^{-k_2t}$
Midilli *et. al* model	$MR= ae^{-kt}+bt$
Two term exponential model	$MR= ae^{-kt}+\left(1-a\right)e^{-kat}$

3.5 Analysis of *gundruk*

3.5.1 Proximate analysis

3.5.1.1 Moisture content

The moisture content was determined by using hot air oven method as per Ranganna (1986).

3.5.1.2 Crude protein

The crude protein was determined by using Kjeldahl`s method. 2 g fatless samples was digested, steam distillated after decomposing the former NaOH. Titration of entrapped NH_3 boric acid was done with standard acid as standard method of Ranganna (1986).

3.5.1.3 Crude fat

The fat content was determined by Soxhlet method as standard method of Ranganna (1986)

3.5.1.4 Total Ash

Ash content was determined using muffle furnaces. 5 g of weighed sample in silica crucible was charred, ashing was done in muffle furnace at 550°C to the constant weight. The difference in weight was the total ash content remaining in crucible, under standardized condition as per Ranganna (1986)

3.6 Data Analysis

The data obtained during the course of experiment was first processed and then analyzed. The experimental data of the ratio of moisture were used to fit the models. For mathematical modeling, the different semi theoretical equations were tested to select the best model for describing the drying curve equation of the curry leaves. The goodness of fit of the tested mathematical models on the experimental data was evaluated using coefficient of determination (R^2), chi-square test (χ^2), Root Mean Squire Error (RMSE) and sum of squared errors (SSE) with higher R^2 values and lower χ^2, RMSE and SSE values indicating a better fit.

Part IV

Results and discussion

Gundruk obtained after fermentation was subjected to cabinet drying. In cabinet drying, the sample was dried under temperature of 50°C, 55°C and 60°C. Change in weight was recorded at the interval of 15 min for cabinet drying process and at the interval of 1 hour for solar drying process until the change in weight becomes negligible. Drying rate curve was obtained by plotting dimensionless moisture ratio (MR) with time (h). The obtained curve was compared with different standard drying curve to obtain model parameters. Parameters of experimental curve closely related with theoretical curve was considered as best-fit model. Lumped parameter (i.e. effective moisture diffusivity) analysis was carried out under the above drying methods and conditions.

4.1 Proximate composition of *gundruk*

Gundruk prepared from rayo was subjected to proximate analysis for the determination of moisture, crude protein, crude fiber and total ash content. The results are tabulated in Table 4.1

Table 4.1 Proximate composition of *gundruk*

Parameters	Value % (db)
Crude fat	2.3 (0.76)
Crude protein	30 (0.32)
Ash	0.72 (0.053)
Crude fiber	54.01 (0.78)

The value of crude protein, fat, crude fiber and ash content of dried sample of *gundruk* was found to be 30%, 2.3%, 54.01%, and 0.72% respectively which is comparable with the analysis carried out by Shrestha (2002) i.e. 33%, 2.1%, 57.68%, and 0.68% respectively.

4.2 Drying behavior of *gundruk*

The drying behavior of *gundruk* is shown in Fig. 4.1 and Fig. 4.2

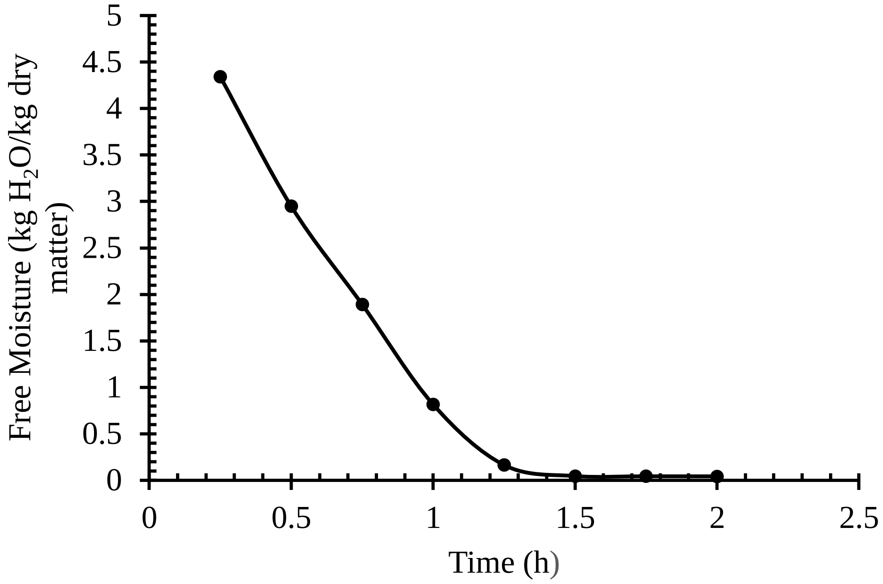

Fig. 4.1 Drying rate curve of *gundruk* showing free moisture as a function of time

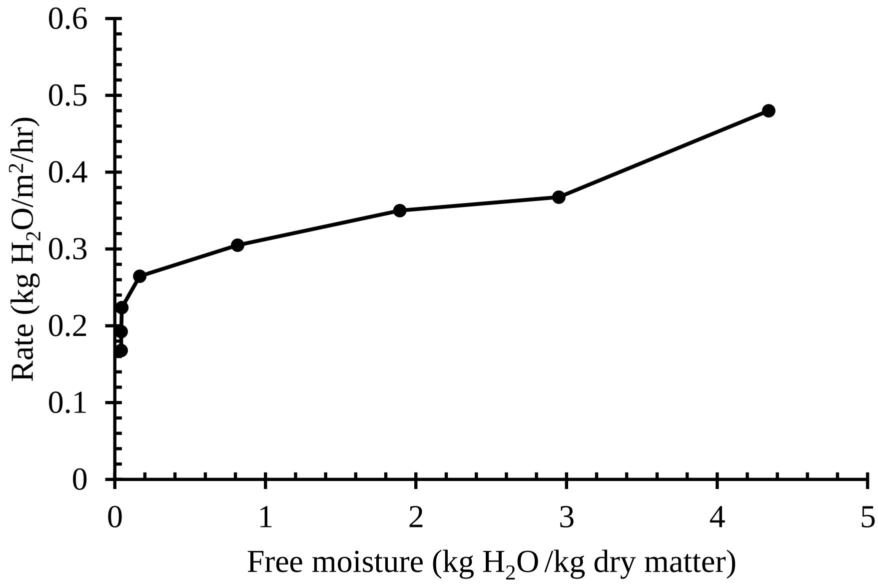

Fig. 4.2 Drying rate curve of *gundruk* showing drying rate as a function of moisture content.

From Fig. 4.2, it was clear that drying rate of *gundruk* falls in falling rate period. That means, critical moisture content was not found on the drying rate curve. The drying rate was decreased and less moisture was available at the surface to evaporate. The food surface is no longer saturated with moisture. That means, a layer of water on the surface of product is disappear and hence falling rate starts.

Mathematical modeling of the process of convection drying of high moisture food is more difficult because initial moisture content is higher and shrinkage occurs during drying. There are mainly two approaches to this complex phenomenon.

One group of the researchers assume that the first period of drying does not occur in drying of such products because the first period terminates in a very short time, thus the changes in water content cease to be linear after a short period from the beginning of drying. Due to this behaviour, the researchers prefer to model the convection drying of vegetables, fruit, and grass by using differential equations of internal mass diffusion or semi-empirical exponential equations developed to account for the second period of drying of grain (Demir *et al.*, 2004).

Pabis (1999), who presented an alternative approach to the convection drying of the products with high initial moisture content, such as vegetables and mushrooms, found the former approach flawed and argues that nonlinearity of changes in water content that occur during the initial period of convection drying of these products cannot justify the claim that the first period of drying does not exist. He maintained that non-linearity is primarily due to drying shrinkage.

Nevertheless, the approach adopted by the first group of researchers is still strong and there are many studies conducted in recent years on the convection drying of very high moisture food that takes into consideration only the second period of drying.

4.2.1 Drying behavior of *gundruk* in cabinet drying

Five thin layer drying models listed in section III were applied to describe the drying kinetics of *gundruk* through the fit to the experimental data. The drying parameters and constants were determined for each drying test. The drying curves of *gundruk* dried at three different temperatures i.e. at 50°C, 55°C and 60°C under cabinet dryer was found in Fig. 4.3**.**

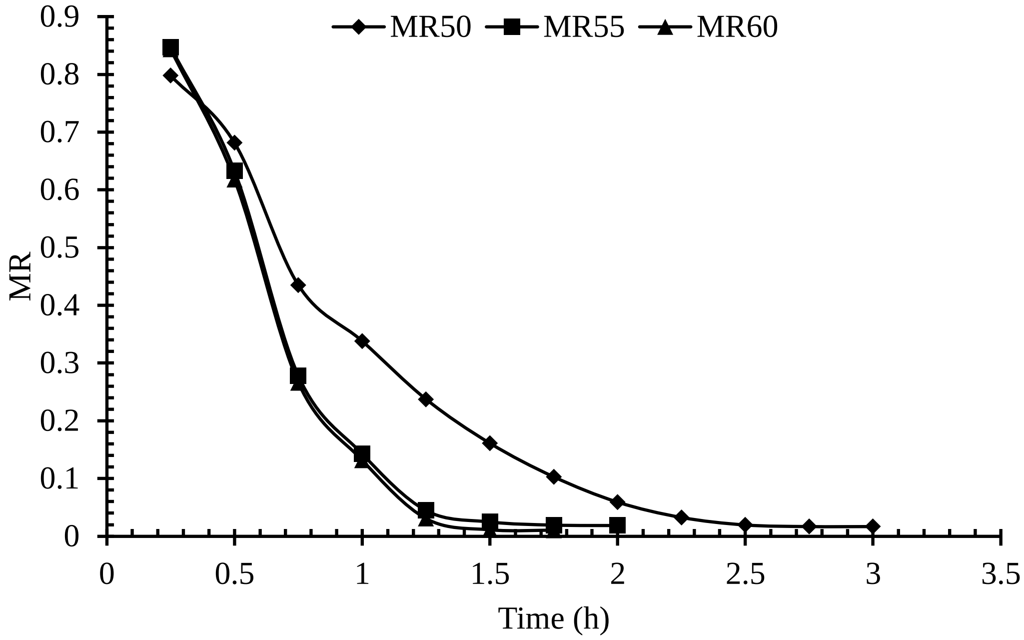

Fig. 4.3 Variation of experimental MR at 50°C, 55°C, 60°C with time during cabinet drying.

Fig. 4.3 showed three distinctly different drying curves for three different drying temperature of similar pattern. However, rate of these drying curve are different i.e. higher the temperature more will be the drying rate and shorter will be the time to reach equilibrium moisture. In addition, higher drying temperature leads to the higher values of moisture diffusivity. It has also been reported by Prabhanjan *et al.* (1995) that the higher drying temperatures provided a larger water vapor pressure deficit or the difference between the saturated water vapor pressure and partial pressure of water vapor in air at a given temperature, which is one of the driving forces for drying.

4.2.2 Drying behaviour of *gundruk* at 50°C

The drying behavior of *gundruk* at 50°C is shown in Fig. 4.4

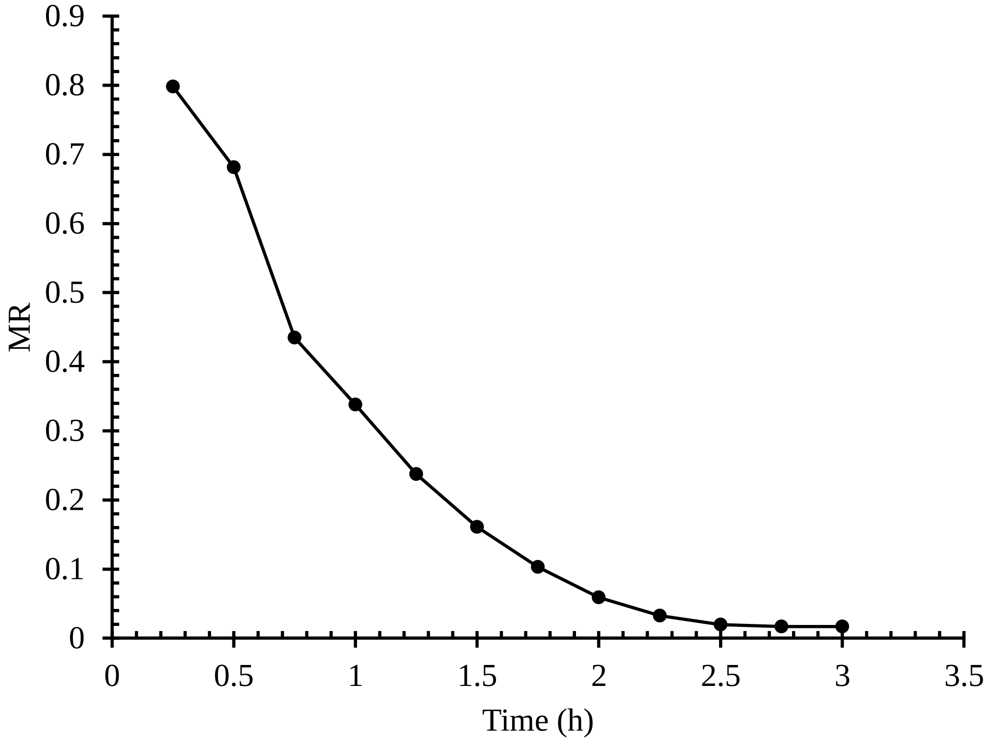

Fig. 4.4 Variation of experimental MR with time at 50°C

4.2.2.1 Statistical Result of Different Models at 50°C

Different parameters and statistical terminologies were used in non-linear regression analysis to identify the goodness of fit. They are statistical coefficient of determination (R^2), reduced chi-square (χ^2), root mean square error (RMSE), sum of squared error (SSE). The statistical results of different models such as coefficient of determination (R^2), the reduced chi-square (χ^2), sum of squared errors (SSE) and the root mean square error (RMSE) are summarized in Table 4.2

Table 4.2 Model parameters determined by nonlinear regression analysis for cabinet drying at temperature of 50°C.

SN	Model name	Constants	R^2	χ^2	RMSE	SSE
1	Modified Henderson and Pabis	a=0, c=k=g=h=1, b=0.024524	0.9811	0.0381	0.1381	0.2286
2	Logarithm	a=0.530277 k=1.11744 c=0.396869	0.991	0.01324	0.996	0.11916
3	Two term model	a=b=0.585562 k_1=k_2=1.303447	0.988	0.00088223	0.02341	0.00705784
4	Midilli	a=0.939443 b=0.000152 k=1.02099 n=1.405146	0.995	0.0000911	0.000779	0.0007288
5	Two term exponential	a=1 k=1.127364	0.991	0.000477	0.0199	0.003816

4.2.2.2 Drying curve model at 50°C

Fig. 4.5 shows graphical representation of experimental MR and theoretical MR with time for best-fit model i.e. Midilli model under cabinet drying at 50°C.

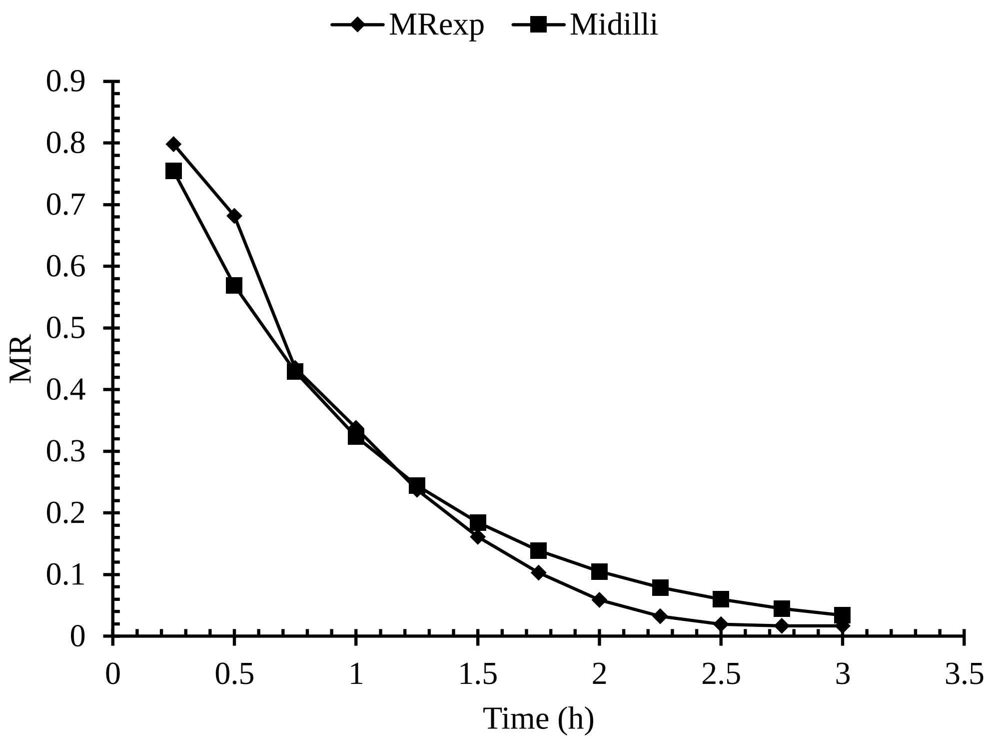

Fig. 4.5 Experimental and predicted Moisture ratio variation with drying time of *gundruk* during cabinet drying at 50^{o}C

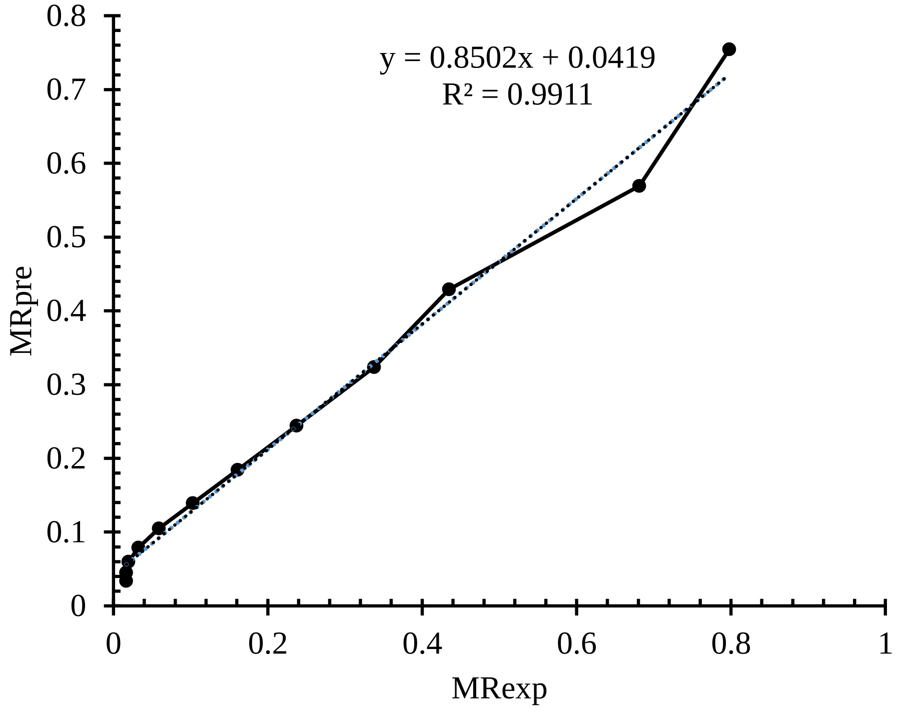

Fig. 4.6 Predicted vs Experimental moisture ratio at 50^{0}C.

4.2.3 Drying behavior of *gundruk* at 55°C

Fig. 4.7 shows the drying behavior of *gundruk* at 55°C

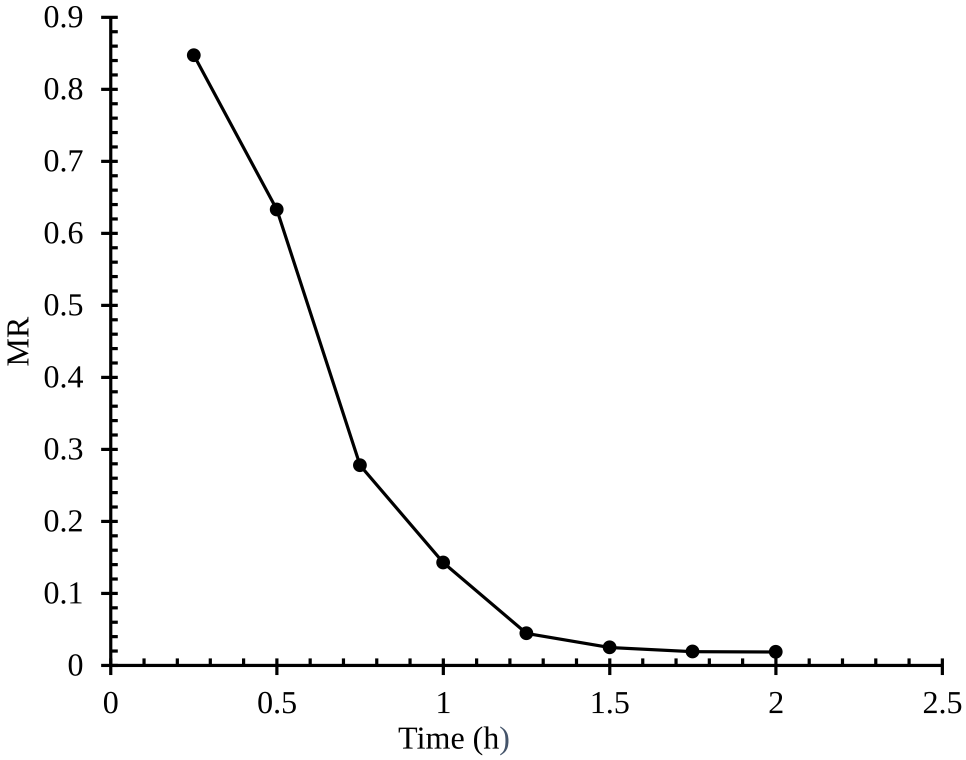

Fig. 4.7 Variation of experimental MR with time at 55°C

4.2.3.1 Statistical result of different models at 55°C

Stastical result for different models at 55°C is shown in Table 4.3

Table 4.3 Model parameters determined by nonlinear regression analysis for cabinet drying at temperature of 55°C

SN	Models	Constants	R^2	χ^2	RMSE	SSE
1	Modified Henderson and Pabis	a=b=c=0.516343 k=g=h=2.199506	0.97224	0.00317	0.057514	0.00634
2	Logarithm	a=1.506708 k=1.898897 c= -0.0521	0.975548	0.000338	0.053982	0.00169
3	Two term model	a=b=0.774512 $k_1=k_2$=2.199499	0.972243	0.001587	0.057514	0.006348

4	Midilli	a=0.927433 b=0.012772 k=2.185182 n=2.339519	0.996	0.000357	0.0211	0.001428
5	Two term exponent	a=0.9999 k=1.522159	0.9699	0.000402	0.060402	0.002412

4.2.3.2 Drying curve model at 55°C

Fig 4.8 and Fig 4.9 shows the drying curve of *gundruk* at 55°C

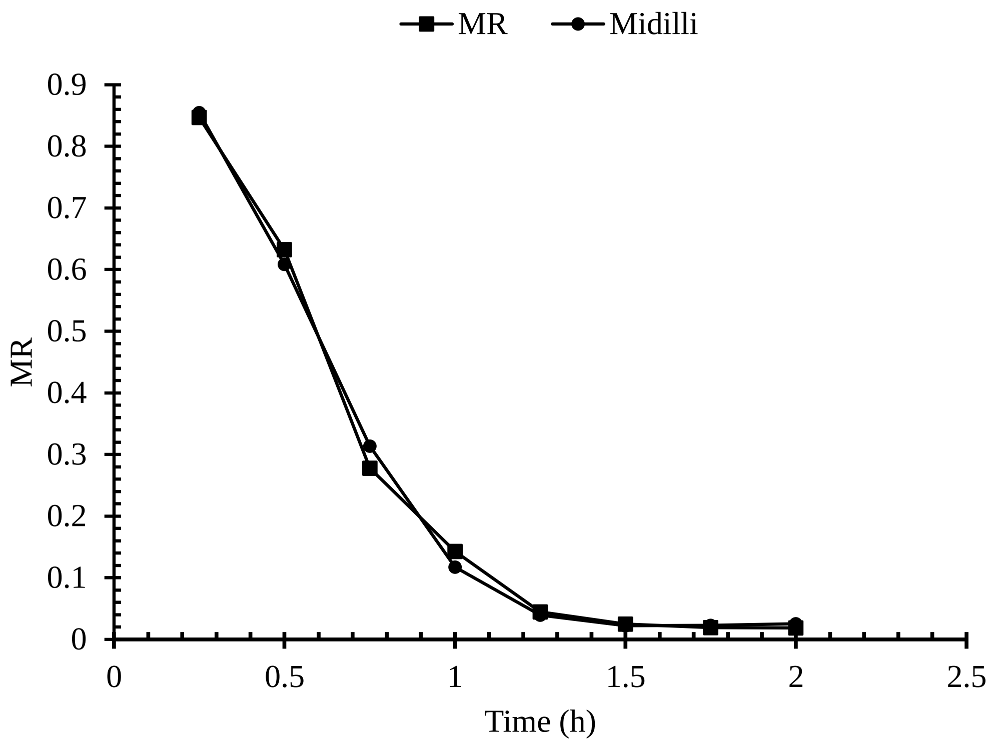

Fig. 4.8 Experimental and predicted Moisture ratio variation with drying time of g*undruk* during cabinet drying at 55°C

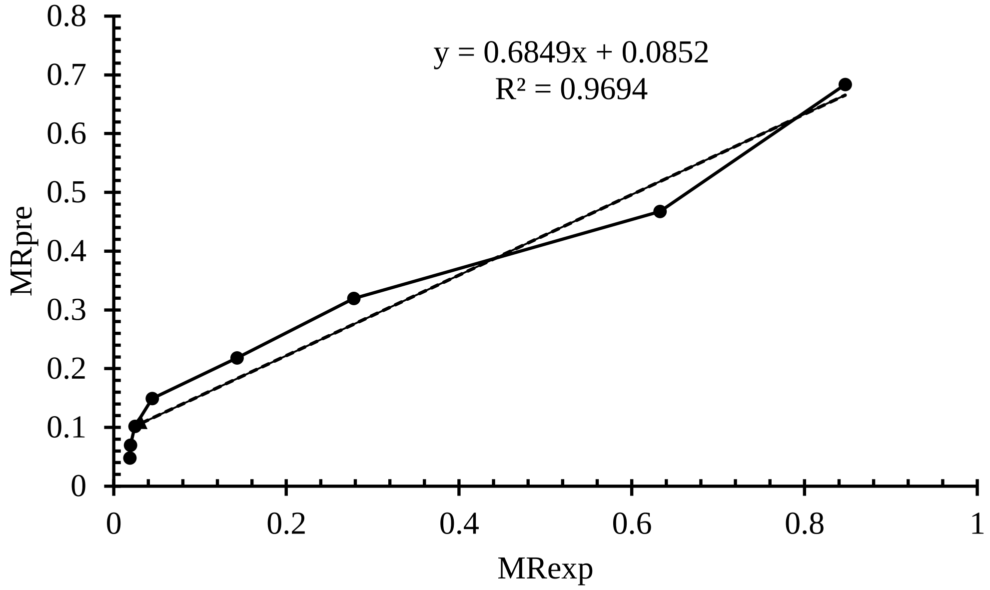

Fig. 4.9 Theoretical vs. experimental moisture ratio at 55°C

4.2.4 Drying behaviour of *gundruk* at 60°C

Fig 4.10 shows drying behaviour of *gundruk* at 60°C

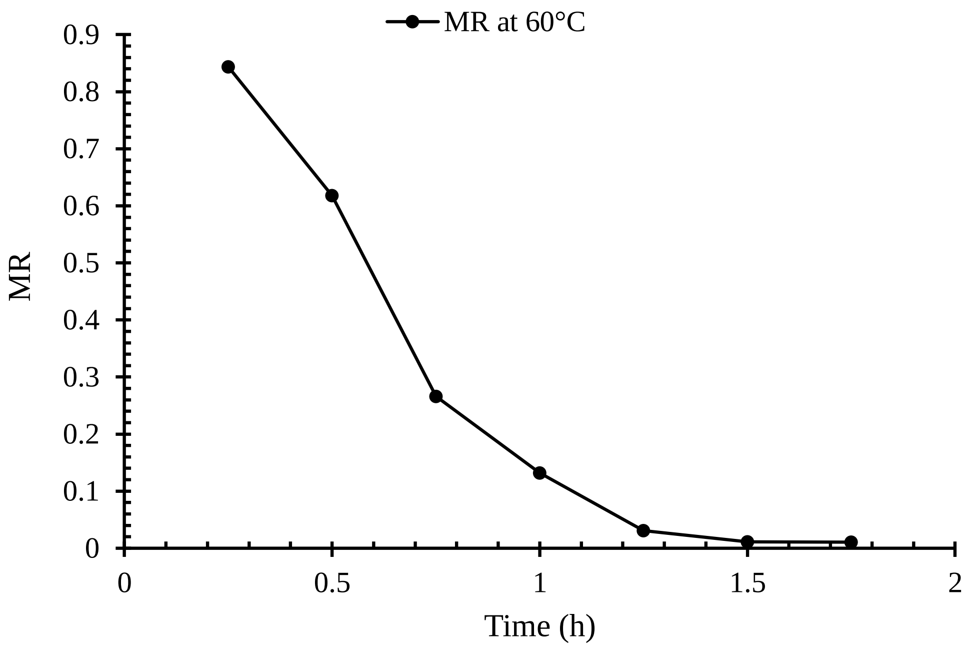

Fig. 4.10 Variation of experimental MR with time at 60°C

4.2.4.1 Statistical results of different model at 60°C

Model parameters for cabinet drying at 60°C is shown in Table 4.4.

Table 4.4 Model parameters determined by nonlinear regression analysis for cabinet drying at temperatue of 60°C

SN	Model	constant	R^2	χ^2	RMSE	SSE
1	Modified Henderson and Pabis	a=b=1.619432 k=g=h=1.366726 c= -1.82401	0.9802	0.000250	0.05111	0.000250
2	Logarithm	a=1.51929 k=1.782586 c= -0.09641	0.9782	0.0000639	0.05365	0.0002556
3	Two term model	a=b=0.406665 k_1=k_2=0.082059	0.92487	0.00828	0.08065	0.02484
4	Midilli	a=0.92537 k=2.264213 b=0.008122 n=2.3477	0.996	0.000012	0.0214	0.000036
5	Twoterm exponential	a=0.999 k=1.561687	0.9764	0.000428	0.055792	0.00214

4.2.4.2 Drying curve model at 60°C

Fig. 4.11 and Fig. 4.12 shows the drying curve at 60^0C

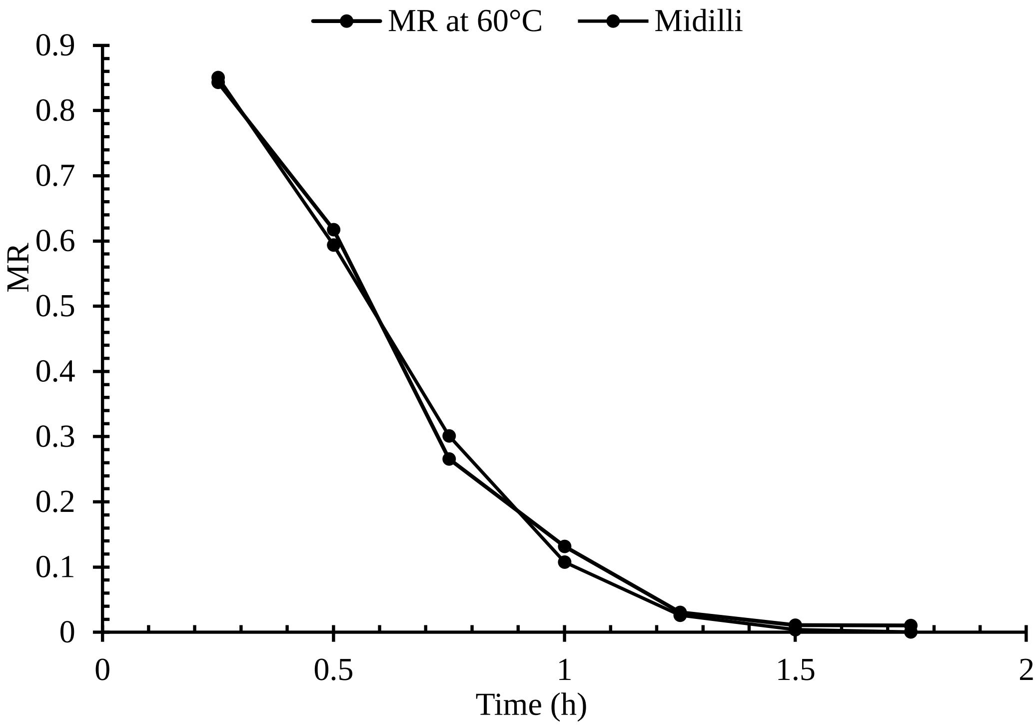

Fig. 4.11 Experimental and predicted Moisture ratio variation with drying time of *gundruk* during cabinet drying at 60°C

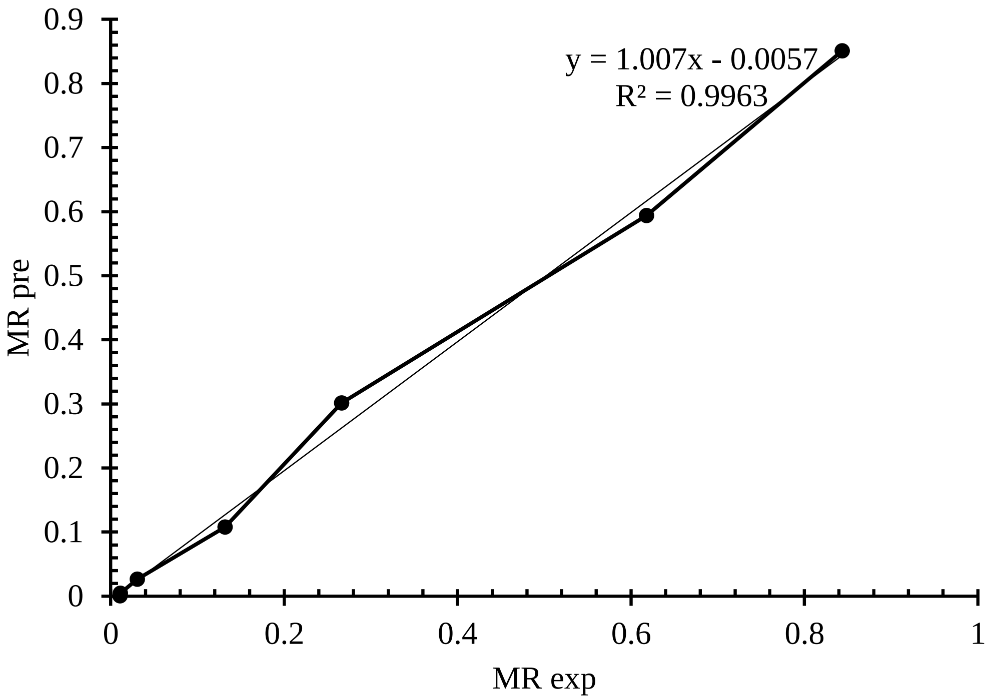

Fig. 4.12 Predicted vs Experimental moisture ratio at 60°C

In all cases, the values of R^2 for the models are greater than the acceptable threshold of 0.90,which indicates a good fit (Madamba *et.al.*,1996). The higher the value of R^2 and the lower the values of, RMSE, χ^2,and SSE are chosen as the criteria for goodness of fit. From the table 4.2, 4.3, and 4.4 it was seen that the value of coefficient of determination ranges between 0.995 to 0.981, 0.996 to 0.945132 and 0.996 to 0.950125 at 50℃, 55℃ and 60℃ respectively. The lowest χ^2 value ranging 0.00003745 to 0.01324, 0.0000338 to 0.001587 and 0.000012 to 0.001736 at 50℃,55℃ and 60℃ respectively. Also the value of RMSE ranging between 0.000779 to 0.996, 0.0211 to 0.080864 and 0.0214 to 0.08117 and the value of SSE ranging from 0.11916 to 0.0007288, 0.006348 to 0.001428 and 0.000036 to 0.0284 at 50°C,55°C and 60°C respectively was found.

At 50°C, the value of R^2 obtained for the Midilli model is higher i.e. 0.995 than those obtained from the other models. Also the values of RMSE, SSE and χ^2 obtained for Midilli model are lower than rest of the models. At 55°C the value of R^2 obtained for the Midilli model is higher i.e. 0.996 and also the values of RMSE, SSE and χ^2 obtained for Midilli et. al. model are lower than rest of the models. At 60℃ the value of R^2 obtained for the Midilli et. al. model is higher i.e. 0.996 on the other hand the values of RMSE, SSE, χ^2 is also lower than other rest of the models.

Variations of experimental and predicted moisture ratio values with drying time are given in Fig. 4.2, 4.5 and 4.8 which shows the moisture ratio values predicted by the Midili model compared with the experimental data for cabinet drying at temperatures of 50°C, 55°C and 60°C. From the figure it clearly shows that the moisture ratio decreases with increasing drying time. At the start of drying process, the rate of moisture removal is very high and decreases as the drying proceeds. The predicted data mainly banded around the straight line which showed the suitability of the model in describing single layer drying behavior of *gundruk*.

Graphical representation of predicted vs experimental MR gives the relation between them. Correlation coefficient (R^2) indicates how well experimental and predicted moisture ratio correlates. Its value should be greater than 0.90 for good correlation. Here, the value of correlation coefficient is close to 1 in all drying temperatures. That means they are well correlated with each other. Here experimental data are generally banded around straight line representing data found computation. This indicates suitability of mathematical model in describing drying behavior of *gundruk.*

The value of R^2 is higher for Midilli model and also value of RMSE and χ^2 are lower for Midilli model too. Hence, Midilli model fits the curve with high degree of accuracy then other models. Hence, Midilli is the best model for simulation of drying characteristic of *gundruk* during cabinet drying at the range of temperature (50- 60)°C. Midilli model has been found suitable in describing the drying kinetics of many fruits and vegetables. This model has found excellent in describing drying kinetics of apple slices corresponding to similar statistical result having the value of R^2, χ^2 and RMSE 0.9979, 1.7×10^{-4} and 0.01357 respectively (zarein *et al.*, 2013). Similarly, Midilli model has been found best fitted in in describing the drying behavior of various porous leaves such as celery leaves, spanich leaves (Simha and Gugalia, 2013). Mint leaves such as spear mint leaves (Ayadi *et al.*, 2014) and also has described the dying kinetics of saffron. This model has also found excellent in describing drying kinetics of various vegetables such as pumpkin and fruits such as jack fruit, kiwi fruit, golden apples (Menges and Ertekin, 2006), mango, ginger and spice like pepper (Onwude *et al.*, 2009).

This Midilli model having three constants have been found best in describing the drying kinetics of different fruits and vegetables as well as savory leaves. According to Onwude *et al.* (2009), this model is noted as most suitable model in over 24% literature sources reviewed. Thus statistical result as well as graphical curve models shows that the midilli *et. al.* is the most suitable drying models that describes the drying kinetics of *gundruk* during hot air convective drying at the temperatures of 50, 55 and 60°C.

4.3 Effective moisture diffusivity

The results have shown that internal mass transfer resistance controls the drying time due tothe presence of a falling rate drying period. Therefore, it is essential to determine the values of the effective moisture diffusivities for given condition. The effective moisture diffusivity was calculated by using the method of slopes. Graphically, it is determined by plotting graph between Ln(MR) with time as shown in Fig. 4.13, 4.14, 4.15 at 50, 55 and 60°C temperature respectively.

4.3.1 Effective moisture diffusivity at 50°C

The effective moisture diffusivity at 50°C is shown in Fig. 4.13.

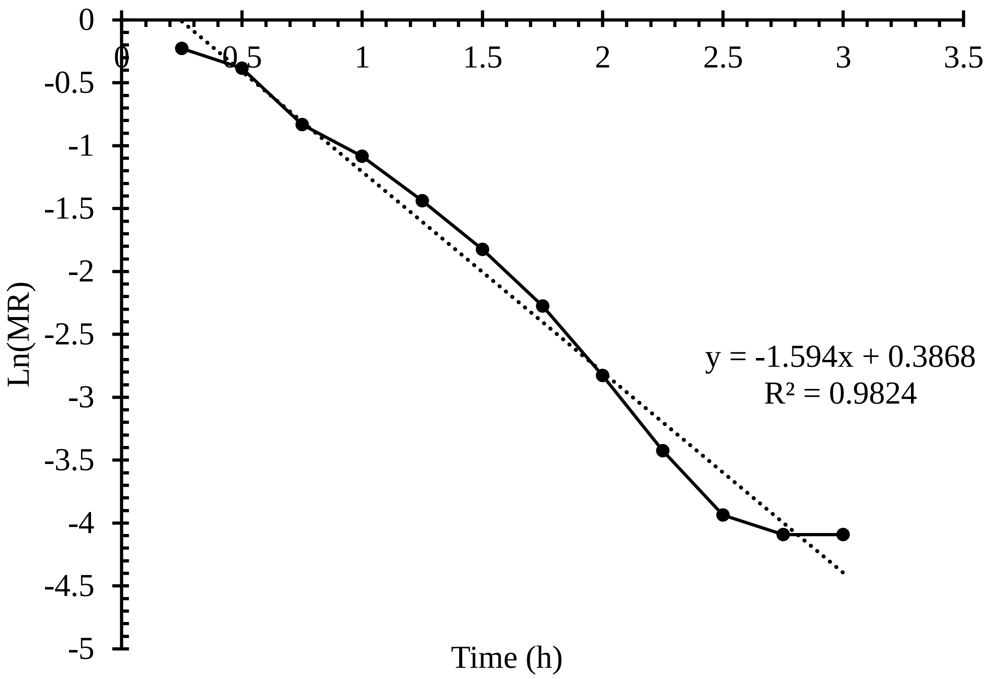

Fig. 4.13 Graphical representation of Ln(MR) vs time at 50°C

Average half thickness of *gundruk*= 1.2×10^{-4} m

Slope (from graph)= -0.6923

Now, slope = $-\frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$

or, $D_{eff} = 4.384 \times 10^{-9}$ m^2/s

The effective moisture diffusivity of *gundruk* during cabinet drying at 55°C was found to be 4.384×10^{-9} m^2/s.

4.3.2 Effective moisture diffusivity at 55°C

Fig 4.14 shows the plot of Ln(MR) and time at 55°C

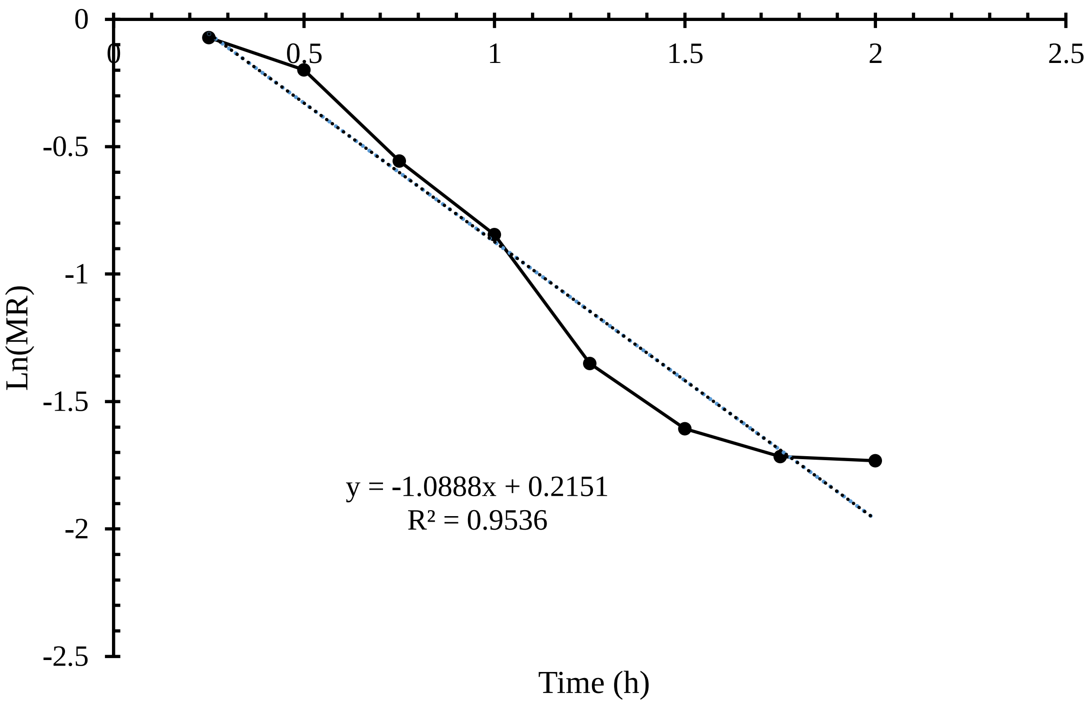

Fig. 4.14 Graphical representation of Ln(MR) vs time at 55 °C

Average half thickness of *gundruk*= 1.25×10^{-4} m

Slope(from graph)= -1.0888

Now, slope = $-\frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$

or, D_{eff} = $6.8949\times10^{-9} m^2/s$

The effective moisture diffusivity of *gundruk* during cabinet drying at 50°C was found to be 6.8949×10^{-9} m^2/s.

4.3.3 Effective moisture diffusivity at 60°C

The plot of Ln(MR) vs time is shown in Fig. 4.15

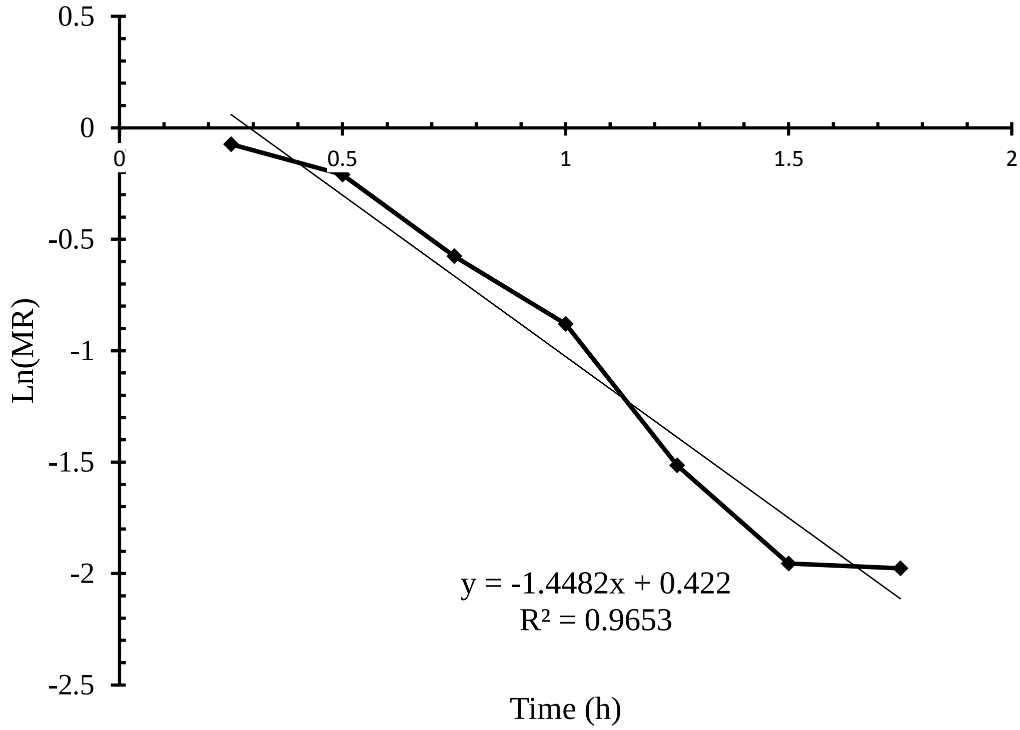

Fig. 4.15 Graphical representation of ln(MR) vs time at 60 °C

Average half thickness of *gundruk*= 1.25×10^{-4} m

Slope (from graph)= -1.4482

Now, slope = $-\dfrac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$

or, D_{eff} = 9.1708×10^{-9} m^2/s

The effective moisture diffusivity of *gundruk* during cabinet drying at 60°C was found to be 9.1708×10^{-9} m^2/s.

The results shows that the effective moisture diffusivity for *gundruk* ranged between $4.384 \times 10^{-9} m^2/s$ for cabinet drying at 50°C, 6.8949×10^{-9} m^2/s for 55 °C and 9.1708×10^{-9} m^2/s for cabinet drying at 60°C. The higher temperature caused an increase of effective moisture diffusivity because of higher mass transfer. These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of i.e. 10^{-9} to 10^{-12} for drying of fruits and vegetables (Ankita and prasad, 2013). Similar results have been obtained for various leaves drying such as spanich , parsley leaves and mint leaves (Akpinar, 2006) A similar observation has been reported for increase in diffusivity coefficient as air drying temperature increases (Rahman and Kumar, 2007).

4.4 Activation Energy

The activation energy is the energy barrier that must be overcome in order to activate moisture diffusion. It is one of the most important terminology that play significant role in drying. By increasing the temperature and hence the drying rate this energy barrier can be easily overcome but there should be a compromise between high temperature and acceptable product quality (Hii *et al.*, 2009). The Arrhenius equation was used to describe the relationship between the effective diffusivity and drying temperature which is shown in Fig 4.16

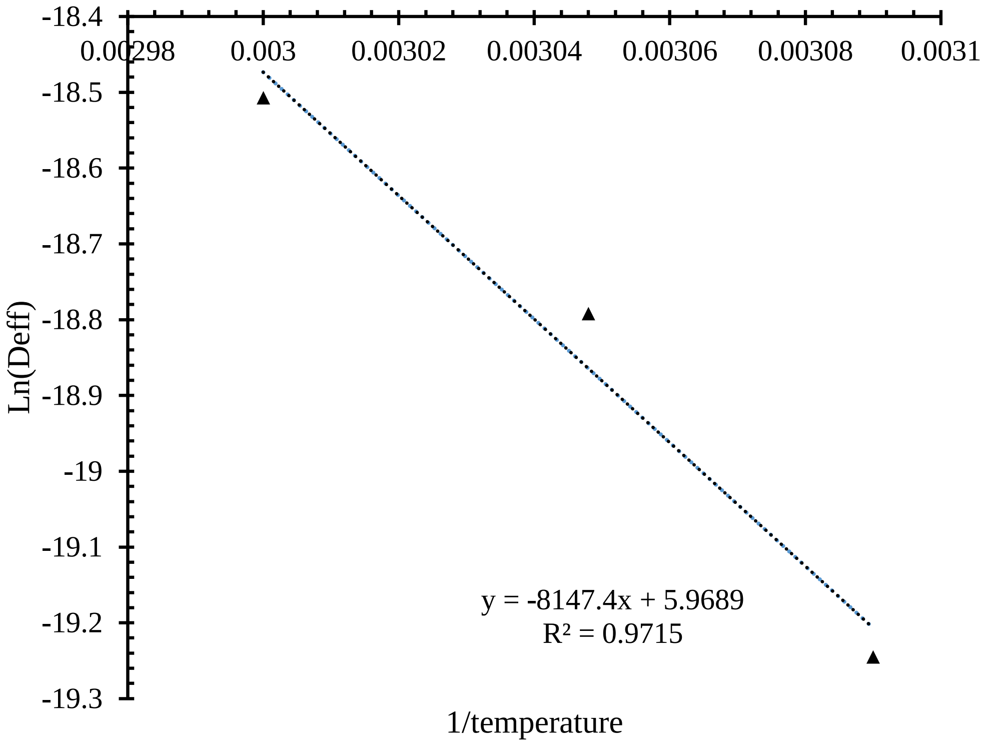

Fig. 4.16 Arrhenius-type relationship between effective moisture diffusivity and the reciprocal of absolute temperature.

We know Arrhenius equation, $D_{eff} = D_o \exp\left(\frac{-E_a}{RT_a}\right)$

Slope= $-\left(\frac{-E_a}{R}\right)$

Now, from graph,

Slope= -8147.4

Ea= 67.737 kJ/mol

Arrhenius factor (D_o) = 391.075 m^2/s

Hence from the Fig. 4.16, it can be concluded that, 67.737 kJ/mol average energy is required to initate the process of the mechanism i.e triggering the moisture diffusivity during *gundruk* drying. The values of activation energy lie from 21 to 110 kJ/mol for most food material (Akpinar and Bicer, 2007). The activation energy is the energy barrier that must be overcome in order to activate moisture diffusion. By increasing the temperature and hence the drying rate this energy barrier can be easily overcome but there should be a compromise between high temperature and acceptable product quality (Hii *et al.*, 2009). The value Activation Energy calculated for *gundruk* drying lies within the value for normal food.

4.5 Drying behaviour of *gundruk* in solar dryer

Drying behaviour of *gundruk* in solar dryer is shown in Fig 4.17 and Fig 4.18 for day 1 and day 2 respecttively

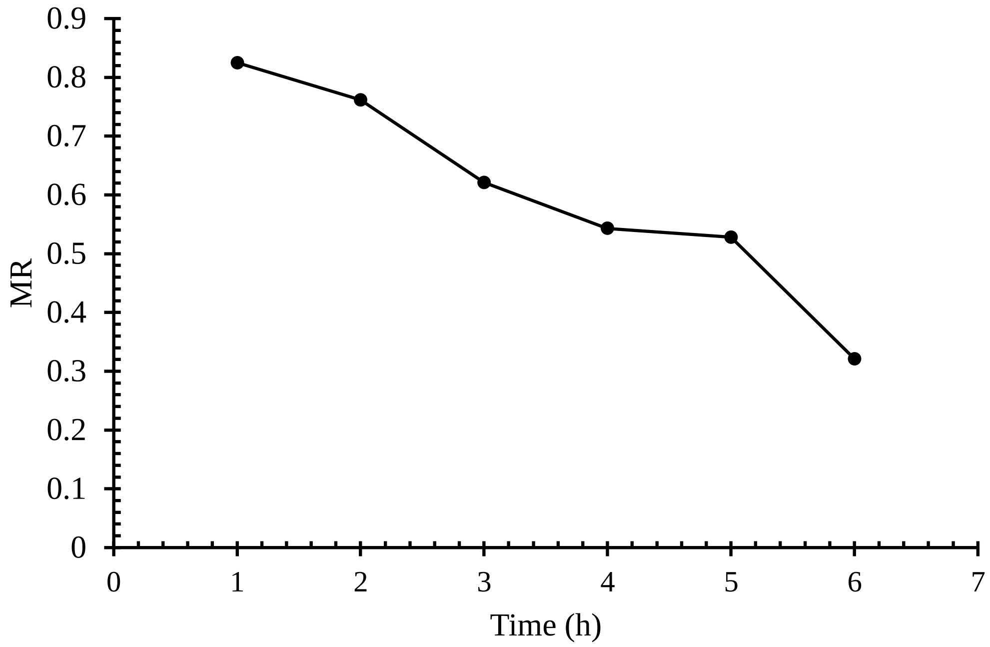

Fig. 4.17 Variation of experimental MR with time during solar drying (Day 1)

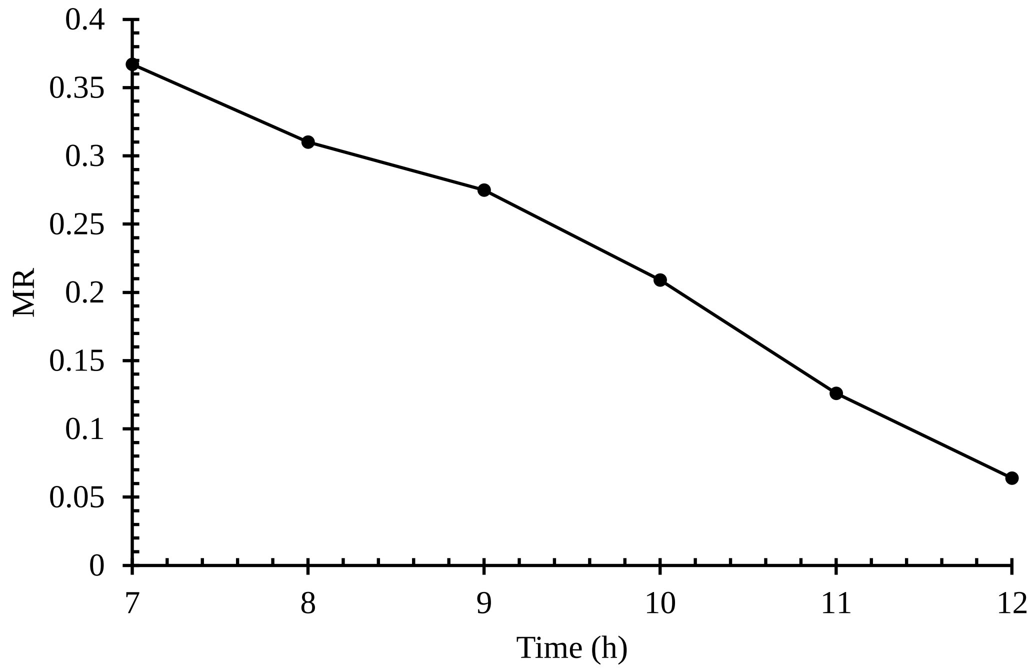

Fig. 4.18 Variation of experimental MR with time during solar drying (Day 2)

Rate of moisture removal continuously decreased with increase in time (Boiln and Salunkhe, 1982).Two drying curves are obtained because of stop of drying at night. During night slight decreased in moisture content occur due to internal heat which is accumulated by product during day and also moisture redistributed within the product and hence increased in moisture occur at the surface of product (Karaaslan *et al.*, 2016).

4.5.1 Statistical result

The accuracy of different semi-theoretical and empirical models to simulate the drying curves of *gundruk* under solar drying was evaluated. In order to mathematically evaluate the simulation, Coefficient of Determination (R^2), Root Mean Squire Error (RMSE), Chi-Square value and sum of squared errors (SSE) value were calculated from comparing the experimental moisture ratio and those given by the proposed model. These results are shown in Table 4.5 and 4.6 for day 1 and day 2 respectively.

Table 4.5 Model parameters determined by nonlinear regression analysis for Solar drying (Day 1)

SN	Model	Constants	R^2	χ^2	RMSE	SSE
1	Modified Henderson and Pabis	a=b=c=0.331247 k=g=h=0.153563	0.92823	0.002358	0.054177	0.011791
2	Logarithm	a=3.352854 c= -2.41308 k=0.03097	0.948027	0.001735	0.046401	0.008516
3	Two term model	a=b=0.496873 $k_1=k_2$=0.153565	0.92823	0.002358	0.054177	0.011791
4	Midilli *et.al*	a=1.101256 b= -0.07621 k=0.181509 n=0.210078	0.947353	0.001703	0.046103	0.008673

5	Two term exponential	a=b=1 k=0.155302	0.927863	0.002363	0.054315	0.011816

Table 4.6 Model parameters determined by nonlinear regression analysis for Solar drying (Day 2)

SN	Model	constants	R^2	χ^2	RMSE	SSE
1	Modified Henderson and Pabis	a=b=c=0.103182 k=g=h=0.289546	0.928513	0.000376	0.02145	0.001878
2	Logarithm	a=3.352854 c= -2.41308 k=0.03097	0.947969	0.000272	0.0183	0.001361
3	Two term model	a=b=0.496873 k_1=k_2=0.153565	0.928513	0.000376	0.02145	0.001878
4	Midilli	a=1.101256 b= -0.07621 k=0.181509 n=0.210078	0.94828	0.000267	0.018253	0.001334
5	Twoterm exponential	a=b=1 k=0.155302	0.9172	0.008994	0.0475	0.4469

Higher the value of R^2 and the lower the values of RMSE, χ^2 and SSE are chosen as the criteria for goodness of fit. From the above table it was seen that the value of coefficient of determination ranges between 0.948027and 0.927863 and the lowest χ^2, RMSE and SSE ranging between 0.001703 to 0.002363, 0.046103 to 0.0.054315, 0.008516 to 0.011791 respectively for first day. The value of R^2 obtained for the logarithm and midilli model is higher i.e. 0.948027,0.947353 than those obtained from other model. Also the values of

RMSE, χ^2 and SSE obtained for logarithm and midilli model are lower than rest of the models. Hence, the best fit model for *gundruk* drying during Solar drying for day 1 is logarithm model and Midilli model for day 2 are shown in Fig. 4.19 and 4.20.

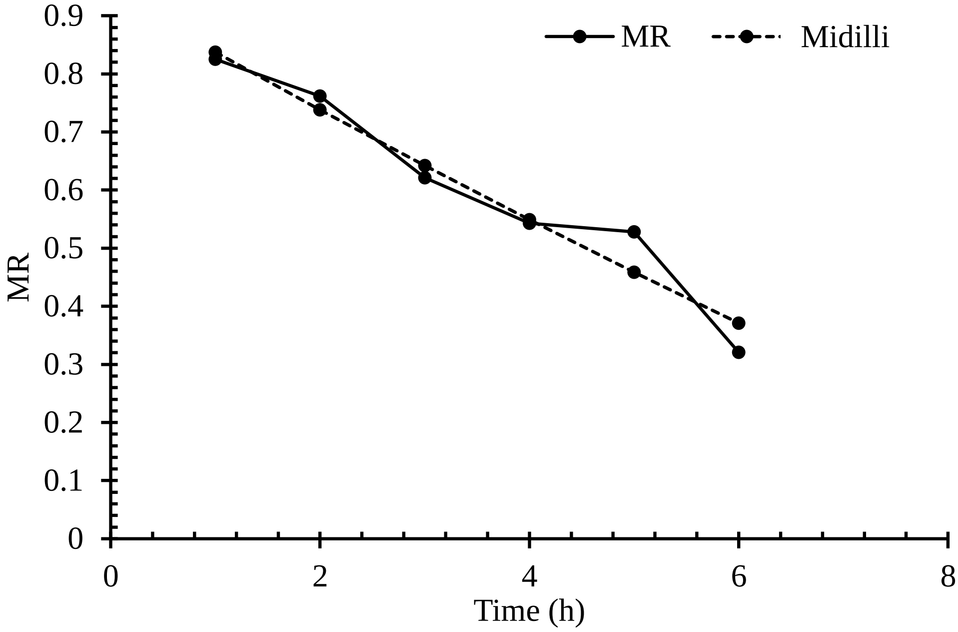

Fig. 4.19 Experimental and predicted Moisture ratio variation with drying time for traditional solar dryer (Day 1)

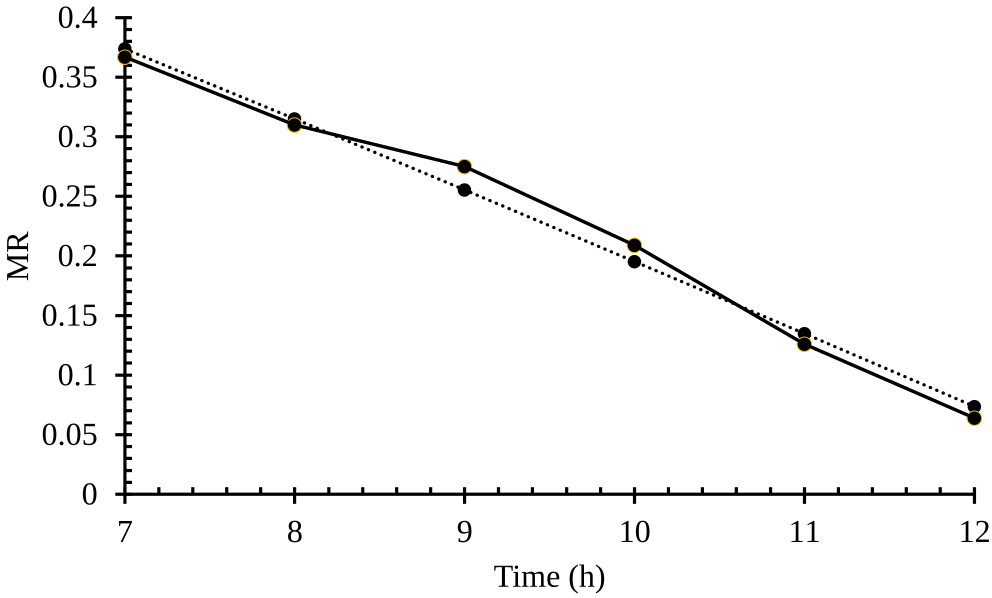

Fig. 4.20 Experimental and predicted Moisture ratio variation with drying time for traditional solar dryer (Day 2)

Fig. 4.19 and Fig. 4.20 shows graphical representation of experimental MR and theoretical MR with time for best fit model i.e. logarithm model for solar dryer for day 1and midilli model for solar dryer for day 2 respectively. From the figure the moisture ratio decreases with increasing drying time. At the start of drying process, the rate of moisture removal is very high and decreases as the drying proceeds.

The theoritical vs. experimental MR for day 1 and day 2 are shown in Fig. 4.21 and 4.22 respectively.

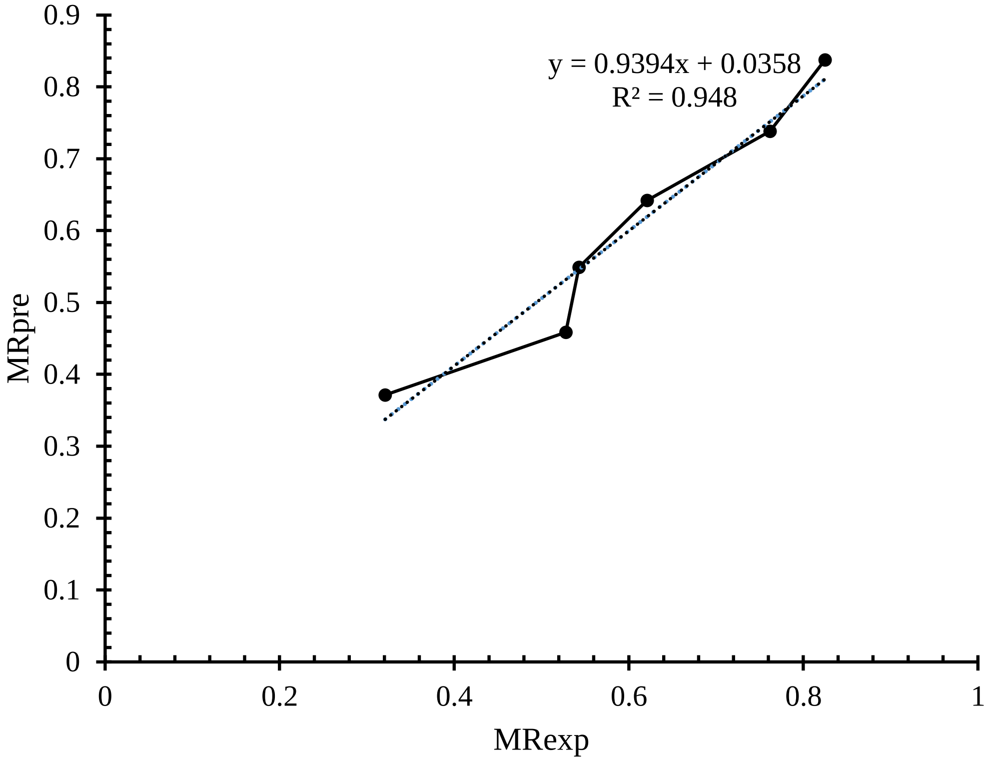

Fig. 4.21 Theoretical vs Experimental Moisture ratio (Day 1)

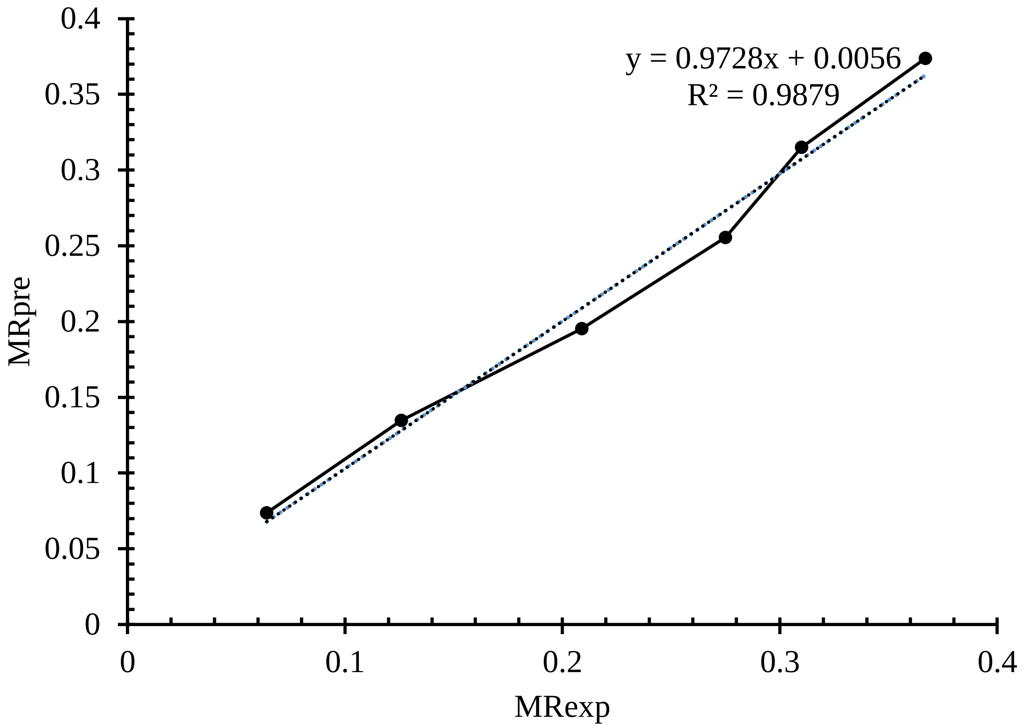

Fig. 4.22 Theoretical vs Experimental Moisture ratio (Day 2)

Graphical representation of predicted vs. experimental MR for solar drying gives the relation between them, which is describe by the equation y = 0.9394x + 0.0358 for day 1 and y = 0.9728x + 0.0056 for day 2. Here, x refers to experimental MR. Correlation coefficient (R^2) indicates how well experimental and predicted moisture ratio correlates. Its value should be greater than 0.90 for good correlation. Here, the value of correlation coefficient is 0.948 (day 1) and 0.9482 (day 2). That means they are well correlated with each other. Here experimental data are generally banded around straight line representing data found computation. This indicates suitability of mathematical model in describing drying behavior of *gundruk*.

The experimental result for solar drying found above are closely related to the result obtain by (Prasad *et al.*, 2006) for drying characteristics of zingiber officinale under open sun and solar biomass (hybrid), (Zomorodian and Moradi, 2010) for mathematical modeling of indirect mode type solar drying Cuminum cuminum, Abdullah and Aydin (2005) for thin layer solar drying and modeling of mulberry and (Hii *et al.*, 2009) for Modeling using a new thin layer drying model and product quality of cocoa.

4.5.2 Effective Moisture Diffusivity

The results have shown that internal mass transfer resistance controls the drying time due to the presence of a falling rate drying period. Therefore, it is essential to determine the values of the effective moisture diffusivities for given condition. The effective moisture diffusivity was calculated by using the method of slopes. Graphically, it is determined by plotting graph between Ln(MR) with time which is shown in Fig. 4.23 and 4.24 for solar drying at day 1 and day 2 respectively.

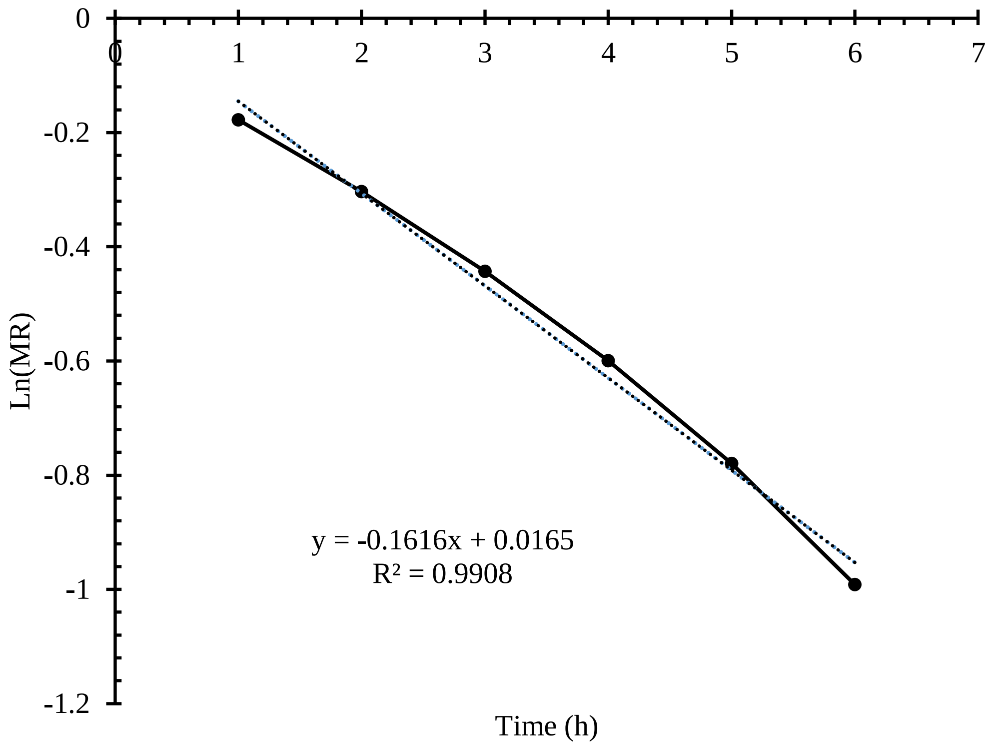

Fig 4.23 Graphical representation of ln(MR) vs. time during solar drying(day 1)

Average half thickness of slab= 1.25×10^{-4} m

From graph,

Slope of curve = -0.1616

Now, , slope = $-\frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$

or, $D_{eff} = 1.0233 \times 10^{-9}$ m^2/s

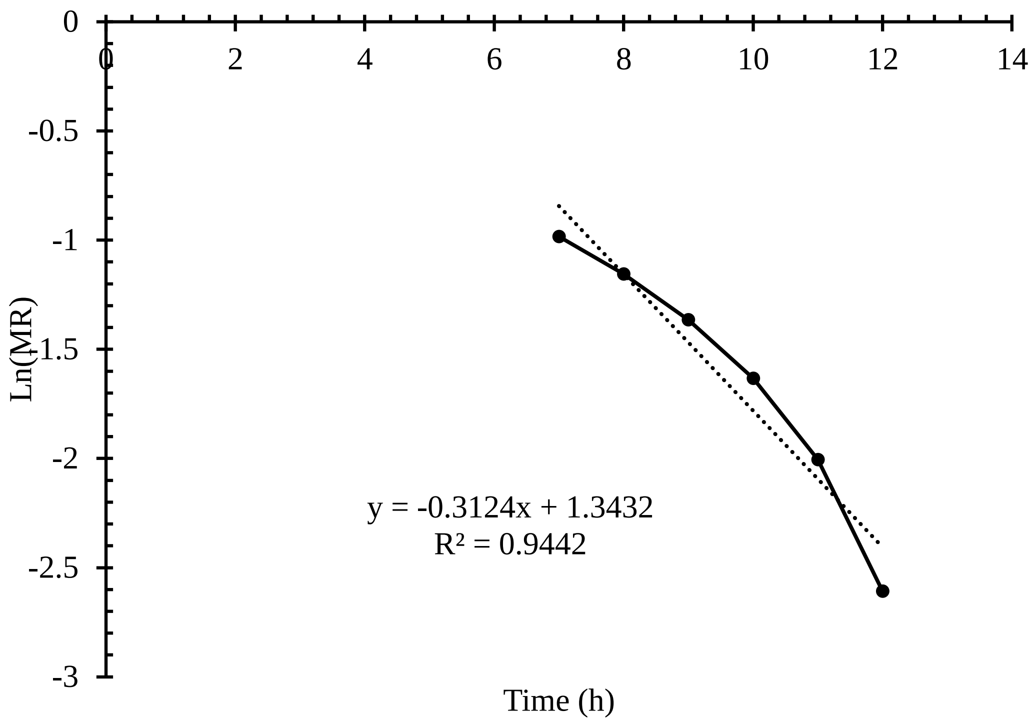

Fig. 4.24 Graphical representation of Ln(MR) vs. time during solar drying (day 2)

Average half thickness of slab= 1.25×10^{-4} m

From graph,

Slope of curve = -0.3124

Now, , slope = $-\frac{\pi^2 D_{eff}}{4\left(h^*\right)^2}$

or, $D_{eff} = 2.298 \times 10^{-9}$ m^2/s

The effective moisture diffusivity of *gundruk* during solar drying was found to be 1.0233×10^{-9} m^2/s and 2.298×10^{-9} m^2/s respectively for day 1 and day 2. These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of i.e. 10^{-9} to 10^{-12} for drying of fruits and vegetables (Ankita and prasad, 2013).

Different literature shows that diffusivity decreased with increase in drying time. That is due to the fact that when the product water content decreases during drying, its water activity also decreases simultaneously (because the remaining water to remove is increasingly bound water).

The result obtain above for moisture diffusivity is closely related to diffusivity obtained by (Samimi *et al.*, 2016) during hot air solar drying of tomato slices ($6.98\times10^{-9} m^2/s$), (Saxena and Dash, 2015) for drying kinetics and moisture diffusivity study of ripe Jackfruit (4.56×10^{-10} m^2/s at 80 ^0C and 1.264×10^{-10} m^2/s at 50°C) and (Rosa *et al.*, 2015) for Mathematical modeling of orange seed drying kinetics whose effective moisture diffusivity ranging from 4.960×10^{-10} to 8.596×10^{-10} m^2/s in the temperature range of 40 – 70°C.

4.5.3 Comparision between Cabinet and Solar drying of *gundruk*

The comparision between cabinet and solar drying of *gundruk* is shown in Table 4.7.

Table 4.7 Comparision between cabinet and solar drying of *gundruk*

	Cabinet drying			Solar drying	
	50^{o}C	55^{o}C	60^{o}C	Day 1	Day 2
D_{eff}	4.384×10^{-9}	6.8949×10^{-9}	9.1708×10^{-9}	1.0233×10^{-9}	2.298×10^{-9}

From the above result it is seen that the moisture diffusivity increases with the drying temperature. D_{eff} is highest at 60^{o}C with value of 9.1708×10^{-9} m^2/s lowest for the solar drying 1.0233×10^{-9} m^2/s. Because the temperature of the solar dryer was less than cabinet dryer. The higher temperature caused increase in moisture diffusivity because of high mass transfer. At high temperature the water molecules are loosely bound to the food matrix, thus requiring less energy to remove than at lower temperature and increasing the air temperature cause more immediate heating within the *gundruk* (increased heat transfer), led to higher vapour pressure in the pores. (Touil *et al.*, 2014).

The 60°C temperature showed the highest drying rate curve Fig. 4.3 as compared to other temperature. Higher the temperature more will be the drying rate and shorter will be the time to reach equilibrium moisture. It has been reported that higher drying temperature provides a large vapour pressure deficit or difference between the saturated vapour pressure and partial pressure of water vapour in air at a given temperature, which is one of the driving forces for drying. Solar drying showed the lowest drying curve Fig. 4.17 and Fig. 4.18 compared to cabinet drying. This may be due to the lower temperature of the solar dryer as compared to the cabinet drying. Lower temperature cause decrease in moisture diffusivity because of low mass transfer. Considering the temperature dependent variable nature of dehydration process, attempts can be made to get the advantage of higher dehydration rate of *gundruk* drying at higher considered temperature in initial phase of drying and to maintain the product quality by lowering the dehydration temperature during the later phase also to reduce the effective dehydration time in order to make the process more economical. This may pave the way for the development of on-line dehydration equipment for getting the product more cheaply and at the same time effective and timely utilization of this valuable highly perishable product to reduce the loss further.

Part V

Conclusions and recommendations

5.1 Conclusion

On the basis of the results obtained, the following conclusions have been drawn;

- The hot air drying method (forced convection air drying) resulted in a higher drying rate and faster drying time than solar air drying (natural convection air drying) of *gundruk.*

- According to drying rate curve, all the drying process of *gundruk* falls in falling rate period which implies that moisture removal from the material was governed by diffusion phenomenon.

- Midilli model best described the drying characteristics of the *gundruk* for cabinet drying at temperature ranging from 50°C, 55°C and 60°C with highest value of R^2 (0.966-0.955)lowest value of $\chi 2$ (0.000012-0.000357), lowest value of RMSE (0.000779-0.0211) and lowest value of SSE (0.000036-0.001428).

- Drying rates of *gundruk* is affected by the temperature. It was that observed drying time decreased as the air temperature increased i.e. lowest drying time at 60°C (105 min) and highest time for solar drying.

- The value of effective moisture diffusivity found is lowest for sun drying i.e. 1.0233×10^{-9} m^2/s and is highest for cabinet drying at 60^0C i.e. $9.170\times10^{-9} m^2/s$. This shows, effective moisture diffusivity value increases with increase in drying temperature. Effective moisture diffusivity also has direct relationship with moisture content.

- The minimum energy required to initate the process of the drying i.e triggering the moisture diffusivity during *gundruk* drying to was found to be 67.737 kJ/mol which is comparable to other leafy vegetables and diffusivity constant was found to be 391.075 m^2/s.

- It is possible to predict moisture content of the product with generalized model showing the effect of drying air temperature on the model constants and coefficients.

5.2 Recommendations

- From this research it will be helpful for the entrepreneur in calculations involving design and construction of new drying system and optimization of the drying process of *gundruk.*
- The effect relative humidity and drying air velocity on drying mathematical modeling of *gundruk* can also be studied.
- Changes in physiological and microbiological properties of *gundruk* at different drying condition and temperature can be carried out.

Part VI

Summary

Gundruk is a non-salted fermented food product prepared by spontaneous lactic acid fermentation of leaves or seedlings of Brassica family, such as radish, cauliflower, rape, mustard, etc. *Gundruk* is one of the most prized typicalindigenous vegetable products and believed to have existed in the Nepalese culture since time immemorial. It occupies an eminent place in the Nepalese diet and is eaten with great relish. *Gundruk* is usually prepared during the months of December to Feburary when the weather is less humid and there is an ample supply of vegetables. Prepared in other seasons, particularly during the monsoon ,it is said to decay rapidly and to have an unpleasant flavor.

Gundruk is the major source of minerals and vitamins during off-season when green vegetables are scarce. *Gundruk* is valued for its uniquely appetizing flavor and served in a number of ways. It is lightly washed, soaked, mixed with onion pieces, oil and salt, and eaten in solid form; or boiled with salt, oil, tomatoes and the soup taken with rice.

Drying or Dehydration is not only energy intensive process. Since it is very critical process, it must be closely controlled in order to get higher quality product with minimum cost and this is possible only if we formulate the whole drying process. A mathematical model is a simplified version of the word that is used to study key characteristics of that word. They are the representation of particular condition. Drying modeling is generally carried out by using thin layer models which are semi theoretical based on Fick's law of diffusion and empirical models.

Gundruk was prepared in a plastic container and after the completion of fermentation it was subjected to different drying conditions. Prepared *gundruk* was than dried under sun, conventional solar drier and cabinet dryer. Under cabinet it was dried at 50, 55 and 60°C. Change in weight was noted in fix interval and is processed. Drying rate curve was plotted between MR and time. The curve obtain were then fitted to twelve different drying models. Proximate composition of *gundruk* was also carried out.

Experimental result showed drying of *gundruk* falls in falling rate period. The rate of drying continuously decreased as drying proceeds. Graphical and statistical analysis of result showed that, Midilli model was best fit model for cabinet drying and Logarithm

model was best fit model for solar drying at day 1 and midilli model was best fitted model for day 2. The R^2, χ^2 and RMSE found for different drying temperature and condition were as follows;

Conditions/values	R^2	χ^2	RMSE	SSE	Fitted model
Solar drying (Day1)	0.948027	0.001735	0.0464013	0.008516	Logatithm
Solar drying (Day2)	0.9428	0.000867	0.01825	0.001334	Midilli
Cabinet drying					
At 60^{o}C	0.996	0.000012	0.0214	0.000036	Midilli
At 55^{o}C	0.996	0.000357	0.0211	0.001428	Midilli
At 50^{o}C	0.995	0.0000911	0.000779	0.0007288	Midilli

The proximate composition of *Gundruk* was obtained as folllows; crude protein, crude fat, crude fiber 30%, 2.1%, 54.01% and ash content 0.72% respectively. The activion energy which is the minimum energy required to initate the moisture removal was found to be 67.737kJ/mol and the value of arrhenius factor (D_0) was found to be 391.075 m^2/s for the *gundruk* drying.

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Appendices

Appendix A.

Experimental MR during different drying conditions

a) Solar drying

Time(hour)(day1)	MR
1	0.852
2	0.762
3	0.621
4	0.543
5	0.528
6	0.321
Time(hour)(Day 2)	MR
1	0.367
2	0.310
3	0.275
4	0.209
5	0.126
6	0.064

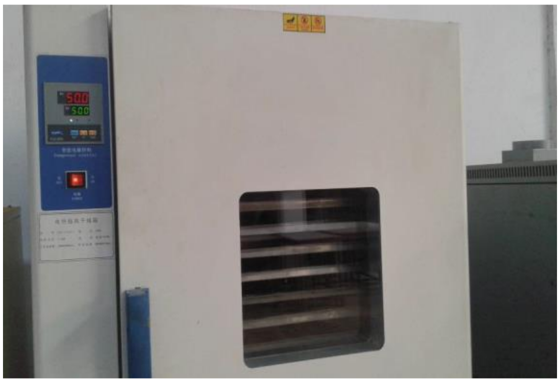
b) Cabinet drying

Time(hr)	MR at 50°C	MR at 55°C	MR at 60°C
0.25	0.7979	0.8471	0.8436
0.5	0.6814	0.6327	0.6117
0.75	0.4350	0.2779	0.266
1	0.3380	0.1428	0.1318
1.25	0.2373	0.04453	0.0306
1.5	0.1611	0.02473	0.0111
1.75	0.1029	0.01924	0.01506
2	0.0591	0.018523	
2.25	0.0325		
2.5	0.0195		
2.75	0.0167		
3	0.0167		

Color plates

P.1 Raw materials for *gundruk* preparation

P.2 *Gundruk* preparation



P.3 Cabinet dryer

P.4 Drying of *gundruk*