**DEVELOPMENT OF COMPUTER SOFTWARE FOR THE ANALYSIS OF DATA FROM AGRO PRODUCTS DEHYDRATION**.****

**Presented to**

**The Department of Chemical Engineering**

**By**

**OLAKUNLE. M. OLORUNFEMI. (180401040)**

**In Partial Fulfillment of the requirement for the Award of**

Bachelor of Science (B.Sc.) Degree

In Chemical Engineering

# ****CERTIFICATION****

This is to certify that this research project entitled “DEVELOPMENT OF COMPUTER SOFTWARE FOR THE ANALYSIS OF DATA FROM AGRO PRODUCT DEHYDRATION” is the original work of Olakunle Micheal Olorunfemi. The research project is submitted to the Department of Chemical Engineering, University of Lagos, Lagos in Partial fulfillment for the award of the B.Sc. degree.

Signature -------------------------------- Date------------------------

**Name**: Olakunle Micheal Olorunfemi

**CERTIFIED BY**

Signature -------------------------------- Date------------------------

**Name:**

*(Project Supervisor)*

**APPROVED BY**

Signature ----------------------------------- Date----------------------

**Name**

*{Programme Coordinator}*

Signature ----------------------------------- Date----------------------

**Name**

*(Head of Chemical Engineering Department)*

# ****LETTER OF TRANSMITTAL****

# ACKNOWLEDGEMENT

# ABSTRACT

An abstract is a summary of your paper and/or research project. It is NOT an introduction to your paper; rather, it should highlight your major points, explain why your work is important, describe how you researched your problem, and offer your conclusions.

Abstracts commonly have these parts: introduction, purpose, method, result, and conclusion. Each part has a different communicative goal or specific function. Most abstracts examined had purpose, method, and result with about half including a clear introduction and conclusion.

**The structure of an abstract typically includes the following sections:**

1. **Introduction: A brief introduction to the topic being investigated**
2. **Purpose: The goal of the study**
3. **Method: An indication of the research methods and approach**
4. **Result: A summary of the major findings**
5. **Conclusion: An explanation of why the findings and key message contribute to the field**

**An abstract is a short summary of a research paper or project, usually about 150–250 words long. It should highlight the major points, explain why the work is important, and offer conclusions**

**Here are some tips for writing an abstract:**

1. **Follow guidelines: Review the formatting and word-count requirements for the conference or publication.**
2. **Focus on clarity: Avoid jargon and overly complex sentences.**
3. **Keep it concise: Leave out unnecessary details and focus on the main points.**
4. **Highlight novelty: Emphasize what sets the research apart.**
5. **Revise: Solicit feedback from colleagues and mentors, then refine until the message is clear**

# TABLE OF CONTENTS

[DEVELOPMENT OF COMPUTER SOFTWARE FOR THE ANALYSIS OF DATA FROM AGRO PRODUCTS DEHYDRATION. i](#_Toc188701012)

[CERTIFICATION i](#_Toc188701013)

[LETTER OF TRANSMITTAL ii](#_Toc188701014)

[ACKNOWLEDGEMENT iii](#_Toc188701015)

[ABSTRACT iv](#_Toc188701016)

[TABLE OF CONTENTS vi](#_Toc188701017)

[ACRONYMS AND ABBREVIATIONS viii](#_Toc188701018)

[LIST OF FIGURES ix](#_Toc188701019)

[LIST OF TABLES x](#_Toc188701020)

[CHAPTER ONE: INTRODUCTION 1](#_Toc188701021)

[1.1 Background of Study 1](#_Toc188701022)

[1.2 Aim and Objectives of Study 3](#_Toc188701023)

[1.3 Scope of Study 3](#_Toc188701024)

[CHAPTER TWO: LITERATURE REVIEW 4](#_Toc188701025)

[2.1 Introduction 4](#_Toc188701026)

[2.2 Historical Review of Drying 4](#_Toc188701027)

[2.3 Basic Theory of Drying 6](#_Toc188701028)

[2.3.1 Mechanisms of Drying 6](#_Toc188701029)

[2.3.2 Drying Phases 7](#_Toc188701030)

[2.3.3 Heat Transfer in Dehydration 10](#_Toc188701031)

[2.3.3.1 General Background 10](#_Toc188701032)

[2.3.3.2 Heat Transfer by Conduction 10](#_Toc188701033)

[2.3.3.3 Heat Transfer by Convection 12](#_Toc188701034)

[2.3.3.4 Heat Transfer by Radiation 15](#_Toc188701035)

[2.3.4 Mass Transfer in Dehydration 16](#_Toc188701036)

[2.3.4.1 Diffusion 16](#_Toc188701037)

[2.3.4.2 Convection 18](#_Toc188701038)

[2.3.4.3 Evaporation 19](#_Toc188701039)

[2.4 Mathematical Model of Drying 20](#_Toc188701040)

[2.4 Thin Layer Drying Models 21](#_Toc188701041)

[CHAPTER FOUR: RESULTS AND DISCUSSION 24](#_Toc188701042)

[4.1 Introduction 24](#_Toc188701043)

[CHAPTER FIVE: CONCLUSION 25](#_Toc188701044)

[REFERENCES 26](#_Toc188701045)

[APPENDICES 27](#_Toc188701046)

[Appendix A 28](#_Toc188701047)

[Appendix B 29](#_Toc188701048)

# ACRONYMS AND ABBREVIATIONS

mm – mass of moisture

# LIST OF FIGURES

# LIST OF TABLES

# ****CHAPTER ONE: INTRODUCTION****

## Background of Study

One common method to preserve agricultural products is drying, in which moisture is removed by evaporation, and simultaneous heat and mass transfer occurs between the sample and the adjacent environment (Kamal et al., 2020). Drying is one of the most ancient and widely practiced techniques for preserving agro-products. It involves the removal of moisture to a level that inhibits the growth of microorganisms and enzymatic activity, ensuring the stability, safety, and longevity of agricultural products (Dhakal, 2022). As a critical post-harvest process, drying also reduces the weight and the volume of food products, which leads to a reduction in the expenses for packaging, storage and transportation.

Drying is an energy-intensive operation. It is estimated to consume 10% to 15% of the total energy requirements of all the food industries in developed countries (Onwude et al., 2016). Studies have shown that dependence purely on experimental drying practices, without mathematical considerations of the drying kinetics, can significantly affect the efficiency of dryers, increase the cost of production, and reduce the quality of the dried product (Onwude et al., 2016). Therefore, it becomes essential to apply mathematical models to estimate the drying kinetics, behavior, and the energy required to dry agricultural products.

One of the mathematical models used in the drying operation is the thin-layer drying model. BUZRUL described Thin-layer drying as the term used for the lumped systems for which a uniform temperature is generally assumed because of the thin structure of the fruit or vegetable that has been sliced before drying (Buzrul, 2022). Thin layer drying models are fundamental to drying simulation. The equation represents moisture exchange between a thin layer of the drying product with its surrounding air. Modeling the thin-layer drying of agricultural products is mainly based on describing the moisture ratio (MR) versus time (t) data using suitable mathematical models.

Fruits and vegetables are highly perishable commodities that needs to be preserved to increase shelf-life. The drying process can be predicted using suitable thin-layer models. Several researchers have studied the drying of fruits and vegetables using thin-layer drying models to estimate the drying time of a product (Onwude et al., 2016). Evidence suggests that these models can further be used to estimate the drying curve and also predict the drying behavior, energy consumption, and heat and mass transfer of the drying process (Murthy and Manohar 2012). However, in practice, there is no single thin-layer model that can be used to effectively generalize the drying kinetics of several fruits and vegetables. This is due to a number of factors including the method of drying, the drying conditions, and the product to be dried (Onwude et al., 2016).

The application of thin-layer drying models to predicting the drying behavior of agro products often involves the measurement of the moisture content of the material. This is done after it has been subjected to different drying conditions (temperature, air velocity, and relative humidity) and subsequent correlation with the dominant drying condition to estimate the model parameters. Incorrect collection of experimental data from the thin-layer drying experiments, will affect the drying process and, subsequently, the selection of appropriate thin-layer models. Thus, the selection of the most suitable thin-layer drying model is also a very important tool in describing the drying behavior of agro products.

Due to the different thin-layer models available and the absence of a single thin-layer model that can be used to generalize the drying kinetics of agro products, it becomes necessary to carefully select the most accurate of these models. Traditional methods of analyzing dehydration data involves manual calculations and the use of generic tools like spreadsheets. While effective, these approaches have several limitations such as time consumption, error prone, and limited automation. The development of a specialized software can address these limitations by automating data analysis of dehydration data by accurately calculating the thermodynamic properties of the product such as enthalpy, entropy, Gibbs free energy, and activation energy. The most accurate thin layer drying model can also be calculated through; fitting of experimental moisture ratio data to various models, comparison of model’s performances using statistical indicators such as the coefficient of determination (R2), root mean square error (RMSE), and sum of squared errors (SSE).

## Aim and Objectives of Study

The aim of this research project is to develop a computer software for the analysis of data from Agro products dehydration. The Objectives of this research project includes:

1. To develop a computer software that accepts experimental dehydration data (moisture ratio and time) in an excel file format.
2. To implement methods for fitting the experimental data to several thin-layer models and determining model parameters.
3. To evaluate the performance of models using statistical indicators such as R² (coefficient of determination), RMSE (root mean square error), and sum of squared errors (SSE).
4. To accurately calculate the moisture diffusivity, activation energy, enthalpy, entropy and Gibbs free energy.
5. To display the results of these analysis in a csv file.

## Scope of Study

1. Conduct a literature review of food dehydration methods.

2. Conduct a literature review on the necessary calculations for food dehydration.

3. Conduct a literature review on methods for fitting data to model equations.

4. Develop software for analyzing dehydration data.

5. Evaluate the performance of models using statistical indicators.

6. Accurately calculate thermodynamic properties from dehydration data.

7. Package the software as an executable file for installation on any computer.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Introduction

The dehydration of agro-products is a vital process in the agricultural and food industry, playing a critical role in extending shelf life, reducing transportation costs, and preserving nutritional value. Accurate analysis of data generated during dehydration processes is essential for optimizing drying conditions and ensuring product quality.

This literature review delves into the theoretical aspects of drying, focusing on mathematical modelling, experimental data interpretation, and computational approaches. It begins by examining the fundamental principles of drying kinetics, highlighting the different thin layer models used such as Newton, Henderson-Pabis, and Page’s models. This literature also highlights the role of computer software in the integration of experimental data with predictive models, facilitating parameter estimation and evaluation of the performance of the different models effectively.

## 2.2 Historical Review of Drying

Drying has been conducted since time immemorial with the main purpose of preserving food and agricultural produce. Although the main objective of drying has not changed since its first application, drying is also used nowadays for a number of other equally important purposes. Among such purposes is the use of drying to produce products that cannot be obtained by other processing means. This ranges from such ubiquitous products as instant milk, coffee, and other beverages to some household products such as detergent powder to some advanced materials, including pharmaceutical products (Devahastin & Jinorose, 2020).

As far as 20000 BC, humans started to dry meat via sun drying. Some 10000 years later, fish was noted to be dried in France, while some grains and legumes were dried in the Middle and Near East. Around 9000 BC, salt was made by drying seawater, but it was only 1500 years ago in India that sugar was first dried into a solid form (Hayashi, 1989). The development of most drying techniques that are widely in use today started only in the nineteenth century. Around 1800, a dryer made of brick, which can probably be regarded as an early version of a mechanical dryer, was constructed and used to dry grains.

In 1856, Gail Borden Jr., based on his earlier experience producing the so-called meat biscuit (Borden, 1856), which was a dehydrated meat mixed with flour, patented a process for concentrating and preserving milk by “coagulating and rearranging the albuminous particles in combination with the evaporation of the fluid in vacuo.” This represents an early attempt to develop a water-removal process under vacuum. Many other patents on the production of various dried products have been filed afterward. For example, in 1865, Charles A. La Mont patented a process to manufacture dried egg (La Mont, 1865).

Another important drying technology, especially for such highly heat-sensitive materials as pharmaceutical products, is freeze drying. A technique similar to freeze drying was first noted to be used by the Peruvian Incas to dry potatoes and other crops and by Japanese monks living on a mountain to dry tofu. In such cases, drying materials were carried high into the mountains where temperatures descended below the freezing point of water; atmospheric pressure was also low due to the high altitudes, resulting in the removal of water within the materials (Hayashi, 1989). Modern-day freeze drying, however, started only in the late nineteenth century, with Richard Altman in 1890 drying pieces of frozen tissues by placing them in a vacuum desiccator at −20 ∘C. Freeze drying became more popular during World War II as a means to preserve blood plasma and eventually vaccines and many other biological molecules (Couriel, 1980).

With the advent of industrialization in the 19th century, drying technology evolved significantly. The development of mechanical dryers such as drum dryers and cabinet dryers, marked a shift from traditional methods to controlled drying processes. These innovations provided better control over drying parameters like temperature and humidity, improving the quality and efficiency of the drying process.

## 2.3 Basic Theory of Drying

In general, drying a solid means the removal of relatively small amounts of water or other liquid from the solid material to reduce the content of residual liquid to an acceptably low value. Drying is usually the final step in a series of operations, and the product from a dryer is often ready for final packaging (McCabe et al., 1993, pp. 767).

The liquid content of a dried substance varies from product to product, occasionally the product contains no liquid and is called bone-dry. More commonly, the product contains some liquid. Dried table salt, for example, contains about 0.5 percent water, dried coal about 4 percent, and dried casein about 8 percent. Drying is a relative term and means merely that there is a reduction in liquid content from an initial value to some acceptable final value (McCabe et al., 1993, pp. 767).

The main objective of drying is to increase the lifetime of food materials. Reducing the moisture content, a reduction of water activity is achieved which reduces the enzymatic activity, inhibits the microbial growth and the progression of undesirable chemical reactions (Delgado & da Silva, 2014). In some cases, drying means an improvement of the organoleptic properties of the food making it more desirable to the eyes of the consumer. Examples include dried fruits, vegetables, nuts, and many other snacks, as well as specific types of meat or fish (Delgado & da Silva, 2014).

As a natural consequence from a loss of water, the dried product has less weight and a smaller volume when compared to fresh one, which facilitates its packaging and transportation, factors that, from an economic point of view, are very important.

### **2.3.1 Mechanisms of Drying**

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 multiphase, heat, mass and momentum transfer phenomena (Kudra and Mujumdar, 2002; Yilbas et al., 2003).

The fundamental mechanism of moisture transfer is due to four major modes of transfer namely (Ibrahim Dincer & Calin Zamfirescu, 2016).

1. Capillary flow of moisture in small interstices.
2. Moisture diffusion due to concentration gradients.
3. Vapor diffusion due to partial pressure gradients.
4. Diffusion in liquid layers adsorbed at solid interfaces.

In general, capillarity is most applicable to coarse granular materials, while liquid diffusion rules single-phase solids with colloidal or gel-like structure. In many cases, the two mechanisms may be applicable to a single drying operation, that is, capillarity dominating moisture movement in the early stages of drying, while taking over at lower moisture contents (Brennan et al., 1976).

### **2.3.2 Drying Phases**

In a drying process, the moisture content is generally determined on a dry material basis. More exactly, when the weights of the moist and dry materials are compared, the mass of moisture is determined. The ratio between the mass of moisture (mm) and the mass of dry material (ms) represents the moisture ratio in percent on a dry basis; this is also denoted with the symbol MR or W. The variation of dry basis moisture ratio is usually measured versus the drying time (Ibrahim Dincer & Calin Zamfirescu, 2016). Moisture ratio typically ranges from 0 to 1.

Figure 2.1a shows the typical variation of moisture content during drying for a general case when a moist solid loses moisture. During the drying of a moist solid in heated air, the air supplies the necessary sensible and latent heat of evaporation to the moisture and also acts as carrier gas for the removal of the water vapor formed from the vicinity of the evaporating surface. In the diagram from Figure 2.1a, the first part of the process, represented by the curve A-B, occurs by mass transfer from the solid surface. This is a stage of warming up of the solid(s) during which the solid surface conditions come into equilibrium with the drying air.in terms of energy consumption, period A-B often represents a negligible proportion of the overall drying cycle requirements, but in some cases, this may be significant (Ibrahim Dincer & Calin Zamfirescu, 2016).

|  |
| --- |
|  |
| **Figure 2.1**: The drying periods for a solid. (a) Moisture content versus time. (b) Drying rate versus drying time. (c) Drying rate versus moisture content. (The curves are for moist material dried at a constant temperature and relative humidity) |

During this period, the moist material can even take more humidity instead of being dried, depending on the actual conditions. Eventually, the surface reaches such conditions that the humidity diffuses out of the product. The period A-B is governed mostly by transient heat transfer processes which, in function of Biot number value, can be diffusively or convectively controlled.

The process B-C shows a reduction of the moisture content which is approximately linear in time. During this phase, the area of the saturated surface decreases gradually. This is the period of drying during which the rate of water removal per unit of drying surface is essentially constant. Point C, where the constant rate period ends, is known as the point of critical moisture content. During B–C period, the movement of moisture within the solid is rapid enough to keep a saturated condition at the surface, and the drying rate is controlled by the rate at which heat is transferred to the evaporating surface. The surface of the solid remains saturated with liquid water (or moisture) by virtue of the fact that movement of water within the solid to the surface takes place at a rate as great as the rate of evaporation from the surface. This stage is controlled by the heat and/or moisture transfer coefficients, the area exposed to the drying medium, and the difference in temperature and relative humidity between the drying air and the wet surface of the solid (Ibrahim Dincer & Calin Zamfirescu, 2016).

Once the saturated moisture at the surface is completely eliminated, the phase C–D follows during which there is no evaporation at the surface, but rather a diffusion process of the moisture within the solid followed by a convective mass transfer at the solid surface. From point C onward, the surface temperature begins to rise and continues to do so as drying proceeds, approaching the dry-bulb temperature of the air as the material approaches dryness. Therefore, when the initial moisture content is above the critical moisture content, the entire drying process occurs under the constant rate conditions. If it is below the critical moisture content, the entire drying process occurs in the falling rate period solid (Ibrahim Dincer & Calin Zamfirescu, 2016).

Figure 2.1b shows the changes in drying rate versus moisture content on dry basis of the solid. This curve is obtained by differentiation of the W(t) curve from Figure 2.1a. Remark that during the period B–C, the rate of drying is constant, which corresponds with the linear reduction of moisture specific to the evaporative drying. Furthermore, the diffusive drying shows a relatively sharp decrease of the moisture elimination rate. Furthermore, Figure 2.1c shows the variation of drying rate versus drying time.

Drying kinetics refers to the changes of average material moisture content and average temperature with time, unlike drying dynamics which describes changes in the temperature and moisture profiles throughout the drying body. Drying kinetics enables calculating the amount of moisture evaporated, drying time, energy consumption, and so on. These depend to a considerable extent on the physicochemical properties of the material. Nevertheless, the changes in material moisture content and temperature are usually controlled by heat and moisture transfer between the body surface, the surroundings, and the internal structure of the drying material. The change in moisture content with time is influenced significantly by the parameters of the drying process, for example, temperature, humidity (pressure), relative velocity of air, or total pressure (Ibrahim Dincer & Calin Zamfirescu, 2016).

### **2.3.3 Heat Transfer in Dehydration**

#### **2.3.3.1 General Background**

Heat transfer plays a major role in the dehydration of agro-products thus, its understanding is needed to achieve better control and avoid under or over-processing, which often results in detrimental effects on the product characteristics. Heat transfer to or from foods can be attained by direct or indirect methods. Direct methods allow contact between the food and the heating medium while indirect methods involve the use of heat exchangers that isolate the product from the medium used as a source or sink of heat (Sepúlveda & Barbosa-Cánovas, 2003).

Heat is a nonmechanical form of energy transferred between regions of different temperatures. Heat transfer, therefore, is a natural energy transfer process in which energy tends to travel from a hotter point to a colder point to reach an equilibrium temperature. The heat transfer mode governing the process is defined by the physical state of the bodies and their relative position. If a heat gradient exists between two solid bodies in contact, the heat transfer will proceed by conduction. If the same gradient exists between two fluids, or between a fluid and a solid, the energy will be transferred by convection. Finally, anybody with a temperature above absolute zero will radiate energy in the form of electromagnetic waves transferring heat by radiation. Besides the physical state or relative position, other physical properties of the bodies involved in these processes influence the heat transfer rate. Characteristics such as form, size, structure, thermal conductivity, specific heat, density, and viscosity, among others, are of paramount importance in the definition of the behavior of a system (Sepúlveda & Barbosa-Cánovas, 2003).

#### **2.3.3.2 Heat Transfer by Conduction**

Heat transfer in solids or highly viscous materials takes place by conduction (Sepúlveda & Barbosa-Cánovas, 2003). In metallic solids, thermal conduction results from the motion of unbound electrons, and there is close correspondence between thermal conductivity and electrical conductivity. In solids that are poor conductors of electricity and in most liquids, thermal conduction results from the transport of momentum of individual molecules along the temperature gradient. In gases, conduction occurs by the random motion of molecules, so that heat is “diffused” from hotter regions to colder ones (McCabe et al., 1993, pp. 286).

As heat penetrates a body, the interior temperature changes from point to point across time. This period of time is known as the unsteady state period. Later, when heat has traveled all the way across the body and equilibrium in temperatures has been reached, the interior temperature of each point will remain the same with respect to time and will only depend on its relative position inside the body. At this moment, the steady state transfer regime has been reached, and the body is working as a heat conductor with a determined heat flux going through it (Sepúlveda & Barbosa-Cánovas, 2003). Thus, the study of heat conduction can be divided into two main areas; the study of heat conduction in the steady state and the study of heat conduction in the nonsteady state.

##### **2.3.3.2.1 Steady State**

This mechanism can be modeled using Fourier’s law for heat conduction (Equation 2.1), which establishes that the heat flux Qx transmitted through a solid in the direction x is inversely proportional to the thickness x and directly proportional to both the perpendicular transmission area A and to the temperature difference between its two opposite faces ∆T. The proportionality constant needed by this model is the thermal conductivity (K).

|  |  |
| --- | --- |
|  | 2.1 |

The negative sign represents the heat flow from the hottest to the coolest surface, thereby rendering a positive value for the heat flux.

##### **2.3.3.2.2 Nonsteady State**

The study of heat conduction in the nonsteady state is pertinent when calculating processes in which the focus is to heat or cool a body instead of using it as a heat conduction medium. The main concern is to find out how long it will take the hottest point in a body to reach the desired temperature (Sepúlveda & Barbosa-Cánovas, 2003).

Heat conduction in agro-products is frequently a three-dimensional phenomenon, as it has finite dimensions. Mathematically the Fourier’s second law of heat transfer for three-dimensional nonsteady state heat conduction states that:

|  |  |
| --- | --- |
|  | 2.2 |

Where T stands for temperature, t for time, x, y, and z for the distance on the x, y and z axis respectively, and α for thermal diffusivity, which is a physical characteristic of the materials (Sepúlveda & Barbosa-Cánovas, 2003).

#### **2.3.3.3 Heat Transfer by Convection**

Heat transfer within a fluid occurs by convection during which heat energy flows as a result of bulk movement of the fluid due to a temperature gradient. The molecules in the fluid will move due to density changes and will interact with each other at different points of the fluid, exchanging energy (Sepúlveda & Barbosa-Cánovas, 2003). Most processing applications of heat transfer by convection involve steady state transfer from a solid surface to a fluid in contact with it or vice versa. Heat transfer by convection is represented by the Newton’s law of cooling.

|  |  |
| --- | --- |
|  | 2.3 |

Where Q corresponds to heat flux, A to the interchange area, to the difference between the fluid and solid temperatures, and h to the proportionality coefficient, known as the heat transfer coefficient.

Bulk molecular motion can be induced by differences in the fluid’s temperature at different points within it, developing a buoyant force. This process is known as natural convection. The coefficient of thermal expansion of a fluid (β) is the main property governing natural convection. Without the existence of gravity and thermal expansion, natural convection would not be possible. Mixing efficiency in natural convection depends on the temperature gradient. A small temperature difference between the fluid and solid in contact will promote weak currents with a low heat transfer coefficient. On the other hand, when a fluid is forced to flow past a surface by mechanical means such as a pump or a fan, higher velocities are obtained and strong currents are induced regardless of natural convection. High heat transfer coefficients can be reached due to more efficient mixing. This regime is known as forced convection. In practice, forced convection is the most used convective heat transfer mode, as greater heat transfer can be accomplished and better control of the system can be easily established (Sepúlveda & Barbosa-Cánovas, 2003).

Newton’s cooling law states that heat flux is directly proportional to the temperature gradient and contact area, both of which are readily quantifiable. However, several problems arise when determining the proportionality constant ‘h’. This constant depends on several factors, such as the fluid’s density, viscosity, specific heat, and thermal conductivity, the flow’s characteristics (i.e its velocity, natural or forced convection, streamline or turbulent flow) and other physical characteristics of the system such as shape and size.

A basic general dimensionless expression that connects the heat transfer coefficient to particular characteristics of fluids and systems has been proposed. This expression states that the Nusselt number Nu is proportional to the product of the Reynolds (Re), Prandtl (Pr), and Grashof (Gr) numbers (Sepúlveda & Barbosa-Cánovas, 2003).

|  |  |
| --- | --- |
|  | 2.4 |

The Nusselt number is a dimensionless form for the heat transfer coefficient. The other factors involved in this ratio are the thermal conductivity of the fluid ‘k’ and the characteristic dimension of the system d, which is the diameter for a round pipe or the length for a flat surface.

|  |  |
| --- | --- |
|  | 2.5 |

The Reynolds number introduces information about the fluid characteristics and flow regime. It can be considered as the ratio of macroscopic flow to internal friction. When this ratio exceeds a certain value, the inertial force predominates, converting flow from a laminar form into a turbulent one. This number involves the characteristic dimension d, and the fluid’s properties density ρ, viscosity η, and velocity v. For physical properties such as viscosity or density that vary with temperature, the value at the arithmetic mean temperature between the inlet and outlet points will be used (Sepúlveda & Barbosa-Cánovas, 2003).

|  |  |
| --- | --- |
|  | 2.6 |

The Prandtl ratio deals only with physical properties of the fluid and behaves as a physical constant. This expression involves specific heat Cp, viscosity η, and thermal conductivity k.

|  |  |
| --- | --- |
|  | 2.7 |

Finally, the Grashof number represents the ratio of buoyancy to internal friction. This quantity involves the characteristic dimension of the system d, the acceleration due to gravity g, the thermal expansion coefficient β, the density of the fluid ρ, the viscosity η, and the temperature difference between a surface and the fluid ∆T:

|  |  |
| --- | --- |
|  | 2.8 |

#### **2.3.3.4 Heat Transfer by Radiation**

Another way to dissipate energy is by heat radiation. Any body with a temperature above absolute zero emits electromagnetic radiation. The higher the temperature, the more energetic the radiation; therefore, the smaller the wavelength. Heat transfer by radiation does not require a temperature gradient to proceed and therefore occurs constantly throughout nature.

The radiation emitted by any given mass of material is independent of that being emitted by another material in sight of, or in contact with, the mass. The net energy gained or lost by a body is the difference between the energy emitted by the body and that absorbed by it from the radiation reaching it from other bodies.

When bodies at different temperatures are placed in sight of one another inside an enclosure, the hotter bodies lose energy by emission of radiation faster than they receive energy by absorption of radiation from the cooler bodies, and the temperatures of the hotter bodies decrease. Simultaneously the cooler bodies absorb energy from the hotter ones faster than they emit energy, and the temperatures of the cooler bodies increase. The process reaches equilibrium when all the bodies reach the same temperature, just as in heat flow by conduction and convection. The conversion of radiation into heat on absorption and the attainment of temperature equilibrium through the net transfer of radiation justify the usual practice of calling radiation "heat." (McCabe et al., 1993, pp. 398).

The heat flux density exchanged between two parallel plates at temperatures Ts and Ta is given by

|  |  |
| --- | --- |
|  | 2.9 |

Where  is called the emissivity, is the Stefan-Boltzmann constant, and its value is W/m2K4. Ts stands for the absolute temperature of the surface

### **2.3.4 Mass Transfer in Dehydration**

Mass transfer is a process of transporting chemical species from one location to another. During drying, moisture migrates from various cellular locations in the material to the surface of the material due to the concentration gradients. Then, the surface moisture moves to the environment (drying air) through evaporation (Khan et al., 2018). The first process can be defined as an internal mass transport process where moisture moves from one place to another inside the material while the second process can be defined as an external mass transport process where the moisture moves from the material’s surface to the drying air inside the dryer (Khan et al., 2022).

The main driving mechanism of internal and external transport process are Diffusion, Convection and Evaporation (Khan et al., 2022).

#### **2.3.4.1 Diffusion**

Diffusion is a molecular mass transfer process where molecules are randomly moved from regions of a high concentration to regions of a low concentration, in which no molecules have a preferred direction. Two different diffusion processes are involved in the movement of moisture in a material namely capillary diffusion and binary diffusion.

Capillary diffusion: Capillary diffusion is a mass transfer process mainly due to the capillary action of the liquid. The capillary action is created by capillary forces which are the molecular attraction between the liquid molecules and the solid surfaces (Khan et al., 2022). The interfacial pressure difference inside the porous matrix is responsible for raising the capillary actions.

The capillary flow in a porous media can be expressed by Darcy’s law (Datta, 2007):

|  |  |
| --- | --- |
|  | 2.10 |

Where P is the fluid pressure (Pa), u is the Darcy velocity (m/s), kl is the porous material’s permeability (m2), and µ is the dynamic viscosity (Pa.s).

Sometimes, the capillary action can be expresses as a result of negative pressure on the liquid (Datta, 2007). Therefore, the mass transfer (mass flux) of the liquid can be expressed by:

|  |  |
| --- | --- |
|  | 2.11 |

Where is the mass flux of the liquid due to the capillary effects (kg/m2s), and µl is the density (kg/m3) and the dynamic viscosity of the liquid (Pa.s) respectively. P indicates the total gas pressure (Pa), pc indicates the liquid phase capillary pressure, and s is the distance (m).

Binary Diffusion: This is a mass transfer process of gaseous species (vapour and air). The binary diffusion coefficient plays a vital role in expressions the gas species movement from one medium to another. Fuller et al (1966) mathematically expressed the binary coefficient (DAW) of species A to diffuse through a medium W using the following equation.

|  |  |
| --- | --- |
| DAW = | 2.12 |

Where MA and Mw indicate the air and water species molecular weight (g/mol) respectively. P is the external pressure (atm), and are the vapour and air atomic diffusion volume, respectively, and Tf is the average temperature between the material surface temperature and the environment temperature (K).

Binary diffusion coefficients can also be a function of temperature and can be expressed by the Bolz expression as given below:

|  |  |
| --- | --- |
| DAW = | 2.13 |

Where T is the temperature (K).

#### **2.3.4.2 Convection**

One of the dominant mass transfer processes due to fluid motion is convection. Mass transfer due to convection can be expresses by the pressure-driven flow. When a pressure gradient exists in a multiphase porous domain, such as food materials, moisture migrates from the higher-pressure area to the lower-pressure area (Khan et al., 2022). Pressure-driven flow plays a dominant role in case-intensive heating, such as microwave-based heating or cooking process.

#### **2.3.4.3 Evaporation**

Evaporation is a process of phase change from liquid to vapour by the absorbance of heat energy. According to Khan et al (2022), evaporation in a porous medium can occur in three different ways namely

1. Distributed (equilibrium) evaporation
2. Non-equilibrium evaporation.
3. Evaporation in the moving interface at the boundary.

The non-equilibrium evaporation rate () can be calculated by the following equation

|  |  |
| --- | --- |
|  | 2.14 |

Where Mv is the molecular weight of vapour (kg/mol), Pv is the vapour pressure (Pa), R is the gas constant (kg/mol/K), Ke is the evaporation constant (1/s), and Pv,eq is the equilibrium vapour pressure (Pa) which can be calculated based on the sorption isotherm of a specific product.

The evaporation due to density difference between the equilibrium vapour density () and the actual vapour density ) is proportional to the non-equilibrium evaporation (Mercier et al, 2014) and is expressed as follows.

|  |  |
| --- | --- |
|  | 2.15 |

Where Kp is the proportionality constant.

## 

## 2.4 Mathematical Modelling of Drying

Mathematical modeling of drying provides a structured approach to describe and predict the behavior of moisture and heat within a material during the drying process. These models serve several purposes, such as aiding in the design of drying equipment, optimizing operating conditions, reducing energy consumption, and improving product quality (Turan & Fıratlıgil, 2019). They also enable researchers and engineers to simulate drying under different scenarios without the need for exhaustive experimental trials, saving time and resources.

Drying processes are modeled with two main models:

1. **Distributed models**

Distributed models consider simultaneous heat and mass transfer. 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 (Erbay & Icier, 2010).

1. **Lumped parameter models**

Lumped parameter models do not pay attention to the temperature gradient in the product. They assume a uniform temperature distribution that equals the drying air temperature in the product (Erbay & Icier, 2010). This assumption causes errors only at the beginning of the drying process and may be reduced to acceptable values by reducing the thickness of the product (Henderson & Pabis, 1961). With this necessity, thin layer drying gains importance and thin layer equations are derived.

### **2.4.1 Thin Layer Drying Models**

According to the American Natl. Standards Inst. And the American Society of Assoc. Executives (ANSI/ASAE 2014), a thin-layer is a layer of material fully exposed to an airstream during drying. The thickness of the layer should be uniform and should not exceed 3 layers of particles (Onwude et al., 2016). Because of its thin structure, the temperature distribution can be easily assumed as uniform and thus, is very suitable for lumped parameter models (Erbay & Icier, 2010).

Thin layer drying models have been found to have wide applications due to their ease of use and requiring less data unlike in complex distributed models such as phenomenological and coupling coefficients (Madamba et al., 1996; Ozdemir & Devres, 1999). According to Onwude et al (2016), It is imperative to note that the concept of thin-layer drying can be applied to:

1. A single material freely exposed to the drying air or one layer of the material.
2. A multilayer of different slice thickness, provided the drying temperature and the relative humidity of the drying air are in the same thermodynamic condition at any time of the drying process.

Thin layer models may be theoretical, semi-theoretical or empirical.

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 (Onwude et al, 2016). Theoretical models explain the drying behaviors of the product clearly and can be used at all process conditions, while they include many assumptions causing considerable errors (Erbay & Icier, 2010). The most widely used theoretical models are derived from Fick’s second law of diffusion.

Semi-theoretical models are derived from the theoretical model (Fick’s second law of diffusion) or its simplified variation (Newton’s law of cooling). The models assume that the resistance to water diffusion occurs in the outer layer of the product (Ertekin & Firat, 2015). Semi-theoretical models are easier and need fewer assumptions due to the use of some experimental data. On the other hand, they are valid only within the process conditions applied (Fortes & Okos, 1981; Parry, 1985).

Empirical models give a direct relationship between the average moisture content and the drying time. 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 (Onwude et al., 2016). These models do not have any physical interpretation and are wholly derived from experimental data.

#### **2.4.1.1 Models Derived From Newton’s Law of Cooling**

* **Newton model:** This model is sometimes referred to in literature as Lewis model or the Exponential model. It is said to be the simplest model because of the single model constant. In the past, this model has been widely applied in describing drying behavior of several food and agricultural products (Onwude et al., 2016).

|  |  |
| --- | --- |
|  | 2.16 |

where k is the drying constant (s-1), MR is the moisture ratio, M is the dry basis moisture content at any time t, MO is the initial dry basis moisture content of the sample, and Me is the equilibrium moisture content. Furthermore, the Newton model has been found to be suitable in describing the drying behavior of strawberry and red chili (Onwude et al., 2016).

* **Page model:** The page model or the Modified Lewis model is an empirical modification of the Newton’s model, whereby the errors associated with using the Newton’s model are greatly minimized by the addition of a dimensionless empirical constant (n).

|  |  |
| --- | --- |
|  | 2.17 |

Where n is the model constant (dimensionless).

This model has 2 constants and is widely used as the basis for most semi-theoretical thin-layer models. Page model was successfully used to describe the drying characteristics of some agricultural products such as tomato (Doymaz, 2007a), wheat (Rafiee et al., 2008), and dates (Hassan and Hobani, 2000).

* **Modified Page Model:** This is a modification of the page model.

|  |  |
| --- | --- |
|  | 2.18 |

Equation 2.18 is widely regarded as the Modified Page model (II). This model has 2 constants and has been applied in predicting the drying kinetics of mint leaves (Onwude et al., 2016).

* **Otsura et al. Model:** Otsura et al. model is similar to Page’s model and used for thin layer drying of rough rice (Ertekin & Firat, 2015).

|  |  |
| --- | --- |
|  | 2.19 |

#### **Models Derived from Fick’s Second Law of Diffusion**

* **Simplified Fick’s Model**

Kumar et al (2006) described the simplified solution of Fick’s diffusion equation valid for long drying times by

|  |  |
| --- | --- |
|  | 2.20 |

This equation was used to model the think layer drying of bay leaves (Gunhan et al., 2005), apricot (Togrul and Pehlivan, 2002) and apple (Togrul, 2005).

* **Henderson and Pabis model:**

This model is also known as the single-term model. It is the first term of the general solution of the Fick’s second law of diffusion. The Henderson and Pabis (1961) model has been effectively applied in the drying of crops such as corn and millet (Onwude et al., 2016).

|  |  |
| --- | --- |
|  | 2.21 |

Where a represents the shape of the material used (dimensionless).

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).

* **Modified Henderson and Pabis model:**

The modified Henderson and Pabis model is a third term general solution of the Fick’s 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 rate period (Onwude et al., 2016). The second term explains the midway part, and the third term explains the initial moisture loss of the drying process (Erbay and Icier 2010). This model contains six constants and thus, can be regarded as a complex thin-layer model.

|  |  |
| --- | --- |
|  | 2.22 |

Where a, b and c are dimensionless model constants and k, g and h are drying constants (s-1).

* **Logarithmic (Asymptotic) model:**

Chandra and Singh (1995) proposed a new model including the logarithmic form of the Henderson and Pabis model with the addition of an empirical term ‘c’.

|  |  |
| --- | --- |
|  | 2.23 |

Where c is a dimensionless constant.

* **Two-term model:**

This model is the first two terms of the general series 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 stage of the drying process while the second term describes the beginning stage 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, with the constants representing the physical properties of the drying process (Onwude et al., 2016).

|  |  |
| --- | --- |
|  | 2.24 |

Where a and b are the dimensionless empirical constants, and K1 and K2 are the drying constants (s-1).

* **Midilli et al model**:

Midilli et al. (2002) proposed a new model with the addition of an extra empirical term that includes ‘t’ to the Henderson and Pabis model. The new model was the combination of an exponential term and a linear term. They applied this new model to the drying of pollen and mushroom using different drying methods.

|  |  |
| --- | --- |
|  | 2.25 |

* **Demir et al. model:**

This model is a modification of the Henderson and Pabis model and the Logarithmic model. It was proposed by Demir et al. (2007) for drying of green olives. This model contains 4 constants and 3 dimensionless empirical constants.

|  |  |
| --- | --- |
|  | 2.26 |

* **Verma et al. model:**

This model is a modification of the two-term model with 4 model constants. The Verma et. al (1985) model has been used successfully to describe the drying kinetics of parsley and pumpkin.

|  |  |
| --- | --- |
|  | 2.27 |

#### **Empirical models**

Empirical models give a direct relationship between the average moisture content and the drying time. The major limitation to the application of empirical models in thin-layer drying is that they do not follow the theoretical fundamentals of the drying process in the form of a kinetic relationship between the rate constant and the moisture concentration, thus giving inaccurate parameter values. More so, 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 of fruits and vegetables are the

1. Weibull model.
2. Wang and Singh model.
3. Thompson model.
4. Diamante et al. model.

* **Aghbashlo et al. model**:

Aghbashlo et al (2009) proposed a model that effectively described the thin-layer drying kinetics of biological materials. The model was tested on carrot and compared with other available thin-layer drying models. It was found that the model best described the drying behavior of carrot (Onwude et al., 2016).

There is no theoretical basis for this model.

|  |  |
| --- | --- |
|  | 2.28 |

Where K1 and K2 are drying constants.

* **Wang and Singh model:**

This model was developed to describe the intermittent drying of rough rice (Wang and Singh 1978). However just like other empirical models, this model has no physical or theoretical interpretation.

|  |  |
| --- | --- |
|  | 2.29 |

Where ‘a’ and ‘b’ are dimensionless model constants gotten from experimental data.

* **Diamante et al model:**

Diamante et al (2010b) proposed an empirical model for the drying of fruits and just like other empirical models, this model lacks theoretical background.

|  |  |
| --- | --- |
|  | 2.30 |

Where ‘a’, ‘b’, and ‘c’ are model constants.

* **Thompson model:**

This model is an empirical model obtained from experimental data by correlating the drying time as a function of the logarithm of the moisture ratio. It was used to describe the drying kinetics of green peas (Pardeshi et al., 2009).

|  |  |
| --- | --- |
|  | 2.31 |

* **Weibull Distribution model:**

This model has no physical meaning. It is a pure statistical approach and given as the following equation (Ertekin & Firat, 2015).

# CHAPTER THREE: METHODS AND MATERIALS

# CHAPTER FOUR: RESULTS AND DISCUSSION

## 4.1 Introduction

# CHAPTER FIVE: CONCLUSION

# REFERENCES

# APPENDICES

## Appendix A

## Appendix B