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Theme:

Intermittent convective drying of agri-food products: effect on kinetics and energy consumption.

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Dedication

I dedicate this modest work

To my parents, with all my gratitude and gratitudefor their sacrifices .

To all my family especially my grandmother

To my brother and my sister.

To all my teachers each with his name,

To all my friends (RMAD) especially

issam Hasrane.

MIMOUNI AHMED RAMZI

Dedication

To my parents and siblings:

I dedicate my sincere and beautiful words to express my deep gratitude, You are the extended family that supports and carries me through every stage of life.

To my little sister Mouna, the innocent and loving girl, you are my heart and the secret to my happiness. I wish you success and excellence in every step you take. And to the beautiful flower, my niece Mayar, may Allah protect and guide her.

To the two big families, Dubabi and Teggar.

And to my dear friends, Ayoub, Ramzi, and Marwan (RMAD), you have been companions on the path and adventure partners. May our unique and beautiful friendship endure.

Also, I dedicate these words to all my colleagues and friends in the university theater, led by Aymen Mehdadi. Thank you for the enjoyable moments and beautiful memories we have shared together. And to the PhD student Issam Hasrane, may Allah grant him success in his journey and life.

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DEBABI DOUMA

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Nomenclature

Δ	variation	-
ΔE	overall color	-
ΔL	lightness	-
Δa	redness	-
Δb	yellowness	-
MR	moisture ratio	Kg water/kg dry basis
k	constant	-
n	number of the constants used in the model	-
a	constant	-
b	constant	-
$RMSE$	The race of the carrier pigeon is extinct.	-
T	temperature	K
t	time	s
Mt	The absolute moisture content at instant t wet basis	$kg\ eau/kg\ MS$
Mo	initial moisture content	Kg water/kg dry basis
Me	initial absolute moisture content on dry basis	kg water/kg wet basis
W	Moisture content on a wet basis	kg water/kg wet basis
m (Initial):	The mass of the sample after drying process	g
m (Final):	The mass of the sample after being placed in the oven	g
Y	The predicted dependent variable	-
Y_1	The predicted time	min
Y_2	The predicted energy	KWh
α	variable	-
N	the number of experimental run	
V	velocity	m/s
n_0	number of central points	-
ir	intermittency ratio	-
χ^2	minimum reduced chi-square	-
R^2	coefficient of determination	
$MRexp$	Expermentally determined moisture content	*Kg water/kg dry matter*
$MRpre$	predicted moisture content	Kg water/kg dry matter

GENERAL INTRODUCTION

GENERAL INTRODUCTION

Drying of foodstuffs is an important and the widely used method of food processing. Due to the lack of proper and timely processing, approximately one third of the global food production is lost annually. In Algeria, for the past few years, the problem of post-harvest losses of surpluses of several products has become increasingly apparent. In fact, the case of tomato and garlic production has been the focus of the media and has become a national concern. .Several techniques have been practiced to reduce food losses and increase shelf life. Among those techniques, drying is one of the oldest, simple and extensively used methods of preserving food. Modern drying techniques tend to improve drying methods, so new technologies focus on intensification, automation and control of the drying process, which would reconcile economy and quality of drying. . Extensive research on drying biomaterials indicates that intermittent drying provides many benefits. It avoids overheating and destruction of the dried biomaterials and limits the consumption of thermal energy and thus increases the energy efficiency of the drying process.

Intermittent drying is often used as an alternative to continuous drying methods, By allowing the product to rest periodically, the drying process can be more even and less prone to over-drying, which can lead to higher product yields and improved product quality.

The objective of this work is to:

- Enhance the quality of over dried product for consumption using an intermittent drying on a laboratory dryer (A570 air conditioning unit)
- Examine the drying kinetics of rehydrated product, and investigate the effect of different parameters on the drying time and the energy consumption.
- Determine the best validated empirical model for this study

This thesis is divided into into general introduction, 4 chapters and a conclusion., The first chapter will discuss the generalities of drying technology and introduce the intermittent drying technique and its applications.

The second chapter will present a literature review of previous intermittent dying studies.

The third chapter is dedicated to present the materials used to realize the drying experiments and also the methods followed to demonstrate the effect of different drying parameters on drying time and energy consumption.

The last chapter will discuss the results obtained by Statgraphics and software to demonstrate the effect of different drying parameters. Finally, a general conclusion reports the main results obtained during this study.

Chapter I: Generalities of drying technology

I. Drying

I.1 Definition:

Drying is an operation whose purpose is to partially or totally eliminate water from a wet body by evaporation of this water. This operation involves a transfer of heat (a supply of heat allows the phase change of the liquid) and a transfer of mass (the liquid impregnating the solid passes to the vapor state in the drying air). The product to be dried can be solid or liquid, but the final product is always solid [1]. The objective of drying a product is to lower its water content, so that its water activity is brought to a value allowing its conservation at ordinary temperature over long periods (of the order of year).

I.2 Why drying?

Drying is one of the main methods of preserving perishable food items. By removing water, it inhibits the action of microbial organisms such as yeasts, molds, and bacteria that cause spoilage. It is also a necessary step in freezing certain products, as the removal of water reduces their weight and volume. In summary, drying allows for:

- Improved product preservation,
- Facilitated transportation,
- Reduced risks of post-harvest losses,
- Expanded commercial availability of these products throughout the year.[2]

I.3 Drying and energy

In order to dry a product, liquid or solid, it is necessary to provide heat, energy, overall it is considered that drying operations consume about 15% of industrial energy in developed countries. This part is important and we must try to find the means to optimize the processes, in an economic but also ecological approach. All the parts of the same product do not have the same behavior with respect to water. This also varies from one product to another, depending on its biochemical composition: certain structures or molecules retain water more than others. When the product is very wet. the water in it is referred to as "free" and when drying, the free water behaves like pure water. It is enough to vaporize it about 2250 kJ/kg. When the product is dry. the water is retained more by it and it is called "bound". The evaporation of this water is more difficult and requires more energy. During the drying it is first the free water which will be evaporated, then the water more and more bound also the quantity of energy necessary to vaporize the same quantity of water increases during the drying [3].

I.4 Drying history

Drying is a technique that has been used since ancient times for the preservation of agricultural and food products (such as grains, seeds, fodder, dried meats and fish, hams, figs, nuts, tobacco, etc.), as well as for the production of materials (such as adobe bricks, ceramics, pottery before firing, wood, etc.), textiles (washing, dyeing, etc.), and skins. For these traditional applications, natural air drying is still widely used, with artificial drying methods involving the addition of energy being considered complementary and providing greater consistency in the face of climate variability, or offering new services (such as powdered milk or instant coffee, long-lasting dry pasta, etc.). **[4]**

Tableau I.1: Advantages and disadvantages of drying [5]

Advantages	Disadvantages
• The simplicity of the method with generally good yields. • A shelf life of several months for dehydrated foods. • The deactivation of enzymes responsible for food degradation. • Inhibition of microbial growth due to the reduction of water activity. • Its ability to be used for commercial purposes, limiting crop losses. • The reduction of financial and environmental costs associated with transportation due to mass reduction.	• Loss of aromas, vitamins, and pigments. • Browning reactions, superficial hardening, irreversible texture modifications and rehydration capacity. • Loss of volatile constituents and changes in the distribution of moisture in the product. • It is costly, especially in terms of energy. Therefore, it is useful to understand everything that can influence drying, particularly drying rate, in order to reduce the cost of this operation.

I.5 Different drying methods

The drying operation can be done in several ways. The most widely used classification criterion is based on the mode of heat transfer between the product and the heat source. [5].

I.5.1. Open air solar drying : Traditional drying or air-drying is one of the most common and time-consuming methods of food preservation in a large number of countries due to its simplicity and abundance of solar radiation. In this process, solar energy is used to directly heat the products that are placed on a platform (floor, carpet, concrete). They are left until they are dried to the desired moisture content. The principle of air drying is simple, solar radiation falls on the surface of the crop and part of the energy is reflected back to the environment. The energy absorbed by the surface of the crops is converted into thermal energy and increases the temperature of the crop.

Fig I.1 Air drying of aromatic herbs**.**

I.5.2. Infrared drying: Allows rapid heating of products in thin layers; the low penetration of IR into the product qualifies this drying as surface heating, the absorbed heat then diffusing into the product by conduction. It is widely applied in the industry of varnishes, paints and photographic films.

I.5.3. Microwave drying: The transfer takes place thanks to the dielectric properties of the materials. Water is very receptive to this type of heating. The waves penetrate the materials and undergo power attenuation linked to the transfer. It is applied to the drying of ink, paint, adhesives and the vacuum drying of pharmaceutical products.

I.5.4. Spray drying: A liquid or suspension is dispersed as fines droplets in a stream of hot air Examples: manufacture of milk powder, fertilizer.

I.5.5. Solar drying: Uses the energy of solar radiation to heat the product and the surrounding air. Solar collectors can be used to capture and/or concentrate the radiation solar, thereby ensuring an increase in air temperature. It is increasingly used in the food industry.

All these drying methods, with the exception of solar drying, generate energy costs and energy supply equipment that can make their application difficult, costly and even impossible in certain regions: especially in developing countries (DCs). Solar drying is therefore the most suitable mode for developing countries, especially since most of these countries have a fairly large solar energy potential. [5]

I.6 Field of application

If drying consumes so much energy, it is because it is used in many industries. The products concerned often touch our daily lives.

Food industry

A large part of the food we consume has undergone a drying operation. Drying can be a necessary step in the production of the product or a role in food preservation. There are no less than 200 types of industrial dryers in the food sector. Examples include:

- Pasta
- Smoked meat: sausage, ham, etc.
- Cheeses: drying in a controlled environment
- Crystallized sugar is obtained by evaporation
- Vegetables (peas, etc.) and dried fruits (prunes, raisins, apricots, etc.)
- Certain snack biscuits are produced by hot air drying from a corn dough
- Fruit juices are prepared from a concentrate obtained by vaporization
- Salt (mining deposit) is crushed, dissolved, purified before being squeezed and finally dried to become refined salt
- The preservation of many types of grains or vegetables is ensured by drying, such as coffee, cocoa, rice and other cereals, tea leaves, spices, etc.
- Some powder products: cocoa, milk, etc.

Paper industry

- Paper is obtained by drying paper pulp on heated rotating rolls.

Wood industry

Wood that has just been cut and sawn contains a high degree of moisture which makes its immediate use in the correct conditions impossible, otherwise one exposes oneself to changes in the size and shape of the wood.

Construction materials

- Bricks, tiles…..

The ceramic industry

- Plates , bowls, platters,…

Biotechnology and the pharmaceutical industry

- baking powder
- antibiotics
- drying of active ingredients in powder form before tableting.

Foundry

- drying of cores that ensure the elaboration of the interior shapes of the pieces obtained by molding. [6].

I.7 Drying mechanism

To dry a product, it is sufficient to ventilate it with air that is hot and dry enough. An exchange of heat and humidity occurs between this air and the moist product. The hot air transfers some of its heat to the product, which develops a partial pressure of water at its upper surface greater than the partial pressure of water in the air used for drying. This difference in pressure leads to a transfer of material from the surface of the solid to the drying air. Therefore, there are two important factors to control the drying processes:

- The transfer of heat to provide the latent heat of vaporization required
- The movement of water or water vapor through the moist product to extract it from the product.

A moist product can be schematically represented as shown in Figure I.2. The solid has a film of water adhering to its external surface by surface forces.

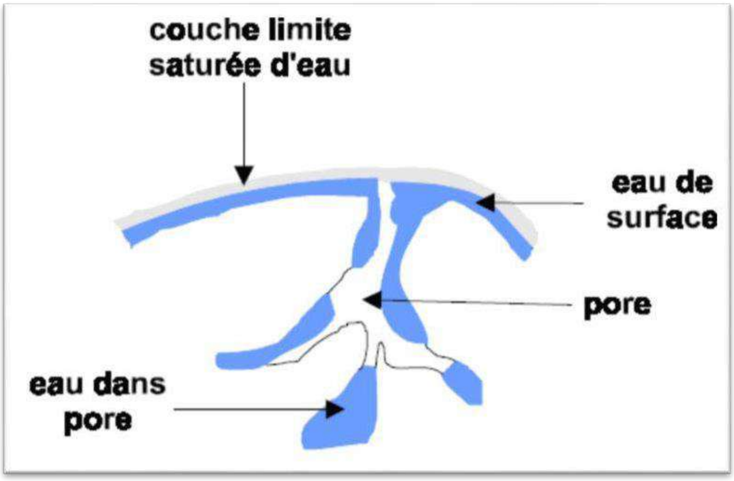

Fig I.2 .Schematic presentation of a wet product [7].

Upon contact with the hot air, the water on the external surface of the product will be evacuated due to the humidity gradient between the air and the product. The osmotic water will migrate to the liquid state from the inside of the grain to this dried periphery due to the osmotic pressure difference. During this migration, air pockets appear to replace the water losses. During drying, cell-to-cell diffusion will be increasingly hindered by cells that tend to retain their water. The last points of humidity will, therefore, be more difficult to remove than the first ones [7].

I.8 Drying periods

The drying process of the hygroscopic material takes place in two stages [8]. The first stage is known as the constant rate period. It takes place at a constant drying rate and generally occurs at the surface of the material when it is saturated with moisture. The surface of the material is maintained at the saturated condition by the rapid movement of the

moisture within the material. The second stage is known as the falling rate period. It occurs when the rate of transport of moisture from the inner structure of the material becomes lowe than the moisture evaporated from the surface of the material. It starts at the critical moisture content, the moisture content corresponding to the end state of the constant rate period. There are two stages of the falling rate period. The first stage falling rate period starts when the surface of the material is not saturated with water or the constant rate period ends, and the moisture diffusion is controlled by the internal liquid movement caused by the concentration of moisture and the internal conditions. The first falling rate period ends when the moisture content of the material reaches the equilibrium moisture content corresponding to the relative humidity of the drying air. The equilibrium moisture content is the moisture content of the product at which the vapour pressure of water in the material is equal to the partial pressure of water in the surrounding air. In the second stage, the dominant mechanism of the mass transfer is the vapour diffusion [9].

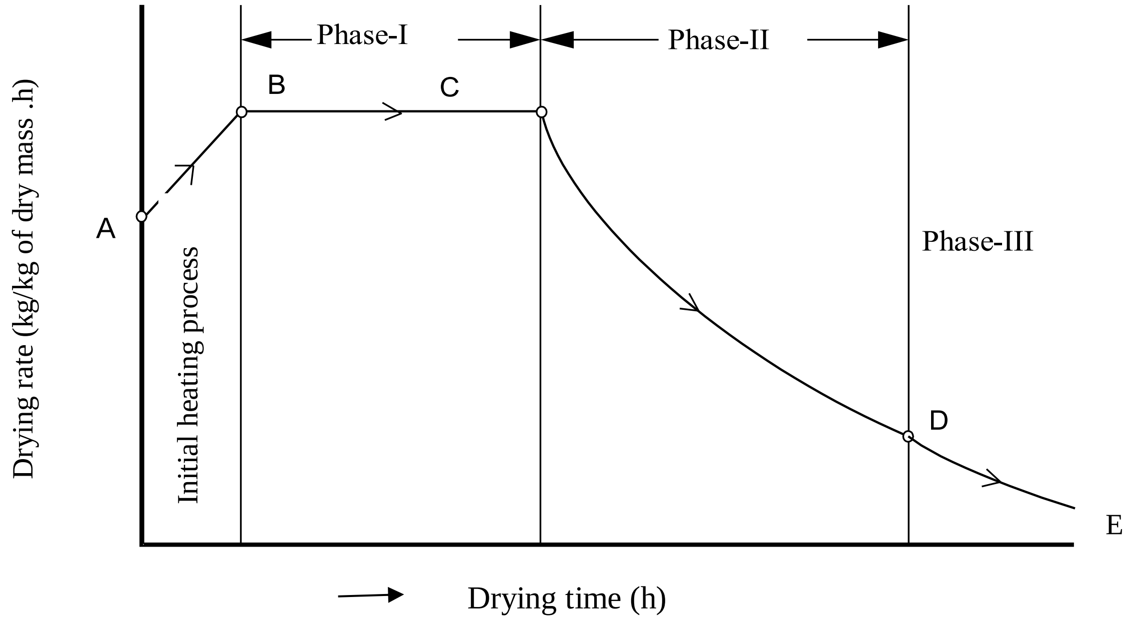

Fig I.3. Drying periods curve [9]

In Fig.I.3, the process AB represents the initial heating process of the material. The process BC represents the constant rate drying process. The point C is known as the critical point from which the falling period rate begins. The processes CD and DE denote the first and the second falling rate periods, respectively. The drying process of most agricultural products occurs in the falling rate periods. [9]

In the end Drying is widely used across various industries, including food, agriculture, and pharmaceuticals. It encompasses multiple techniques that are employed in different fields. One of these techniques is intermittent drying, which is utilized when continuous drying is not feasible or suitable. Intermittent drying allows for better control over the drying process and prevents surface drying without proper interior drying.

I.9 Drying efficiency improvement

Drying is a crucial operation in many industrial sectors, including food, chemical, pharmaceutical, textile, and electronics. However, continuous drying poses some problems that can be solved by using intermittent drying.

One of the main issues encountered during continuous drying is the loss of the nutritional quality of the materials being dried due to their exposure to high temperatures and prolonged periods, which results in the deterioration of vitamins and other nutrients. Additionally, continuous drying requires significant amounts of energy, time, and costs.

Intermittent drying solves these problems by allowing for the adjustment of the material's temperature, control of moisture, and periods of stoppage and cooling, which reduces the loss of nutritional quality and increases production efficiency while saving energy and costs. Therefore, it can be said that intermittent drying is an ideal option for the drying process in various industrial sectors.

I.10 Intermittent drying

It is a drying method where the conditions of drying can be changed and controlled with time. Different intermittency techniques can be applied, but the most common type involves changing drying air conditions. Intermittent drying is preferable for materials that are sensitive to crack formation, and it can be applied in different modes such as on/off mode, periodic variation mode, and ramp variation mode. This method differs from conventional continuous drying methods and improves the heat and mass transfer of the drying process, leading to enhancement of the drying rate [11]

Intermittent drying is often used for heat-sensitive materials or when continuous drying is not feasible or practical. It can be applied in various industries such as food processing, pharmaceuticals, and paper manufacturing. These studies have found several interesting features of time-dependent drying. These features are:

- ✓ thermal energy savings
- ✓ shorter effective drying time
- ✓ higher moisture removal rates
- ✓ lower product surface temperature

- ✓ higher product quality. These include reduced shrinkage, cracking, and brittleness, improved colour and nutrient detention.

The intermittency, a is defned as the fraction of time during which the inlet air temperature is raised to the defned cycle time i.e., ... [10].

I.10.1 Classification of intermittent dryers

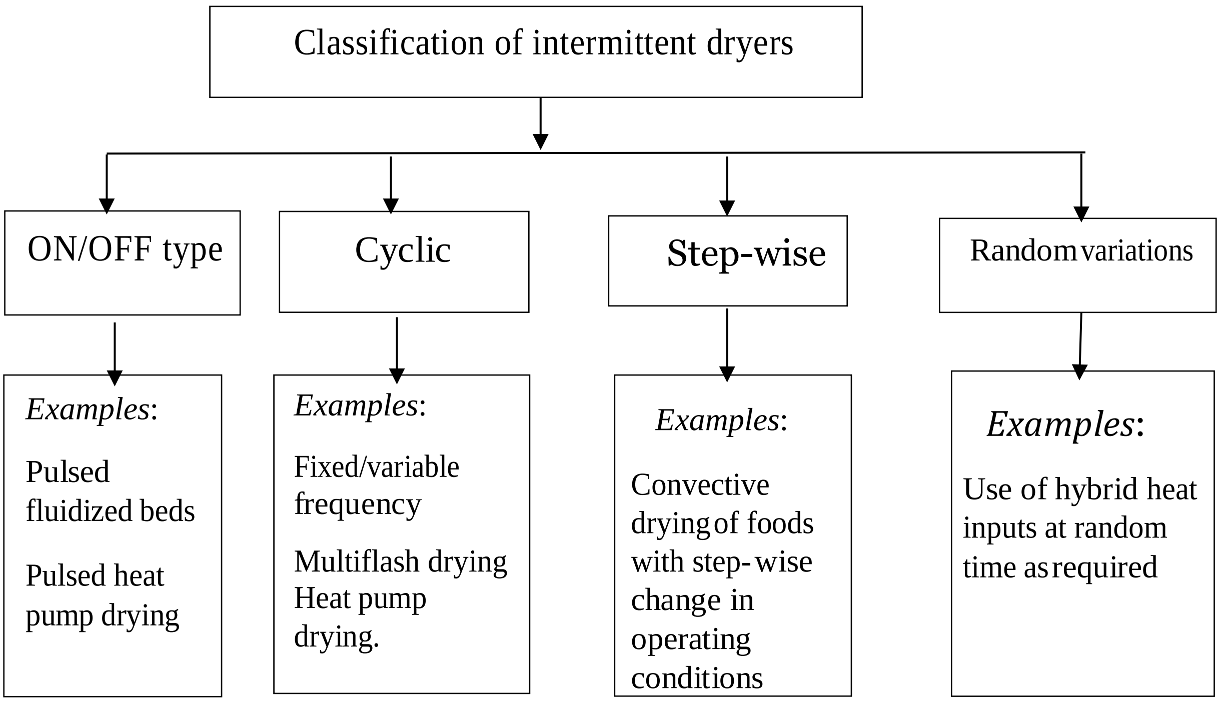

Fig I.4. Classification of type of intermittency. .[11]

I.10.2 Different intermittency modes

I.10.2.1 Step-wise

Stepwise drying is one of the popular drying methods, which can be categorize into step-up drying and step-down drying to optimize the drying process for better quality products. One of the earlier research on optimization of air drying of food was carried which the key optimization problems were pointed out.

Several studies have indicated that intermittent drying accompanied with step-wise temperature profiles could bring improvement in product quality. In cabbage outer leaves study, the results showed that the stepdown drying process able to maximize the product quality and minimize quality degradation compare to continuous drying process.[13]

I.10.2.1 On/off (tempering periods)

The on/off mode of the drying process refers to the alternating periods of operation and rest during intermittent drying. In this mode, the drying system or equipment is switched "on" to initiate the drying cycle, where heat is typically applied to the material, and moisture is evaporated and removed. This is followed by a period of "off" or rest, during which the drying system is inactive, and no heat or drying action takes place.

Various researchers have employed different definitions for the intermittency ratio. Some have defined it as the ratio of the on-time to the off-time of the system, investigating energy savings based on this ratio, the intermittency ratio used is given as : [14]

$$\mathrm{ir} = \frac{\mathrm{ton}}{\mathrm{ton} + \mathrm{toff}} \qquad \textbf{Eq.(I.1)}$$

I.10.2.2 Cyclic variation

Cyclic variation intermittent drying is a drying technique used in various industries to remove moisture from materials or products. It involves a repeated cycle of drying and resting periods, which allows for more efficient moisture removal and can help maintain the quality of the dried material. The drying rates were determined by measuring the moisture content of the samples at different time intervals during the drying process. The drying rates can be calculated based on the change in moisture content over time.

There are differences between cyclic variation drying and stepwise drying. Cyclic variation drying involves repeated cycles of drying and resting periods. These cycles are repeated until the desired moisture level is achieved. This pattern allows for periodic and consistent moisture removal from the material. Stepwise drying, on the other hand, is a sequential drying process that involves gradually increasing drying rates at specific intervals until the desired moisture level is reached. The drying rate is adjusted based on the time or the remaining moisture in the material.

I.10.2.3 Random variation

In the context of intermittent drying, random variation refers to the unpredictable and non-systematic fluctuations or deviations in the drying process. It represents the inherent variability that can occur during the intermittent drying cycles, which is not influenced by any specific pattern or external factors.

Intermittent drying involves cycles of drying and resting periods, as discussed earlier. During each cycle, the drying conditions, such as temperature, airflow, or duration, may be controlled and maintained at specific set points. However, random variation can still occur within these cycles, leading to slight variations in the drying rate, moisture distribution, or other parameters.

I.11 Intermittent dryers

I.11.1 Fluidized bed

Fluidized bed drying involves suspending a column of particulate solids in a flowing gas stream, typically heated air. With increasing gas flow, a point is reached where the drag force imparted by the upward moving gas equals the weight of the particles. An easy way to implement intermittent drying for fluidized bed dryer is to regulate the airflow to the bed in an intermittent manner, Fluidized bed drying (FBD) has found many applications for drying of granular solids in the food, ceramic, pharmaceutical and agriculture industries For drying of powders in the 50–2000 lm range, fluidized beds FBD competes successfully with other more traditional dryer types, e.g., rotary, tunnel, conveyor and continuous tray. FBD has the following advantages :

- high drying rates due to excellent gas–particle contact leading to high heat and mass transfer rates
- smaller flow area
- higher thermal efficiency
- lower capital and maintenance costs compared to rotary dryers; and (e) ease of control.[12]

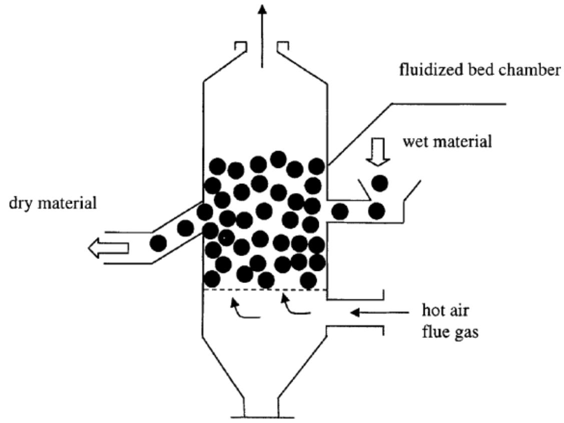

Fig I.5. Well-mixed continuous fluidized bed dryer.[12]

I.11.2 Spouted bed dryer

Spouted bed drying is a type of drying process used to remove moisture from wet particulate materials, such as grains, powders, and pellets. It involves the use of a spouted bed, which is a vertical column filled with particles of the material to be dried.

The process begins by introducing hot air into the bottom of the spouted bed, which then flows upward through the bed. As the air moves through the bed, it causes the particles to spout or circulate, creating a fluidized state. This fluidized state exposes the surface of the particles to the hot air, which then removes the moisture from the particles. The researchers did conducted experiments to investigate the intermittent drying of corn using a rotating jet spouted bed system .

To achieve intermittent drying, the researchers used various drying periods interspersed with long tempering periods. During the active periods, the particles experienced intense mixing and circulation due to the hydrodynamics of the rotating spouts. This resulted in a high intensity of heat and mass transfer, facilitating drying. On the other hand, during the no-flow periods, the temperature and moisture gradients were relaxed, allowing favorable moisture redistribution inside the particles ,They aimed to determine if corn, as a slow drying material, could be dried efficiently with lower energy consumption by implementing an intermittent air schedule.[12]

I.11.3 Microwave dryer

A microwave dryer is a type of drying equipment that utilizes microwave technology for drying various materials. It uses electromagnetic waves at high frequencies to generate heat inside the material, thereby accelerating the evaporation process. The microwave dryer consists of a chamber or cavity where the material to be dried is placed, and microwave energy is directed towards it. The microwave energy heats the water molecules within the material, causing them to evaporate and remove moisture. This type of dryer is commonly used in industries such as food processing, agriculture, and pharmaceuticals, where quick and efficient drying is required. The advantages of microwave drying include faster drying times, preservation of product quality, and energy efficiency.

the reasercher Gong et al. (1998) did conduct a numerical study to investigate the effect of intermittent microwave heating on the drying behavior of clay and the development of internal stresses. Their numerical results indicated that using intermittent microwave heating significantly reduced maximum tensile and compressive stresses within the dried clay compared to continuous heating. Additionally, the time taken for peak stresses to develop was somewhat reduced[15].

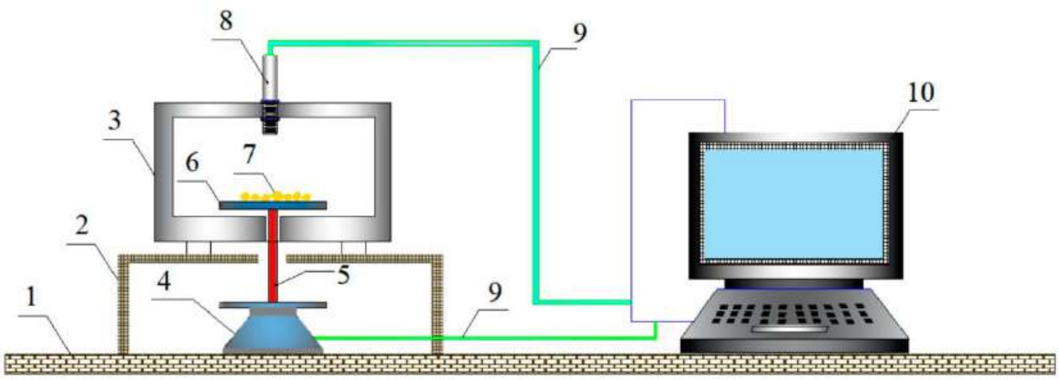

Fig I.6. Schematic representation of the microwave convective dryer.

1_Test bench; 2_Bearing; 3_Microwave oven; 4_Electronic balance; 5_Stents; 6_Tray; 7_Product 8_Infrared thermometer; 9_Cable; 10_Computer

I.11.4 Heat pump dryer

For a batch heat pump drying system, intermittent drying processes can be classified into three categories:

a. intermittent variation of the air temperature
b. intermittent supply of air flow
c. intermittent regulation of the air humidity

and intermittent addition of other energy sources e.g. infra-red, microwave and radio-frequency Among the three, the intermittent regulation of air temperature is considered to have the most

substantial influence on the product drying kinetics and various quality parameters and is the focus of the following sections. The intermittent conditions employed in the studies observed that employing intermittent temperature profile resulted in savings in drying time by about 25%, 48% and 61% for **ir** = ¼ , **ir** = 1/2 and **ir** = 2/3, respective.[16]

I.12 Quality Aspects in intermittent drying

During drying, quality changes in food product are inevitable. Hence, many advances in drying technologies have been practiced during the past decade with the main target of minimizing quality degradation of dried food products. Intermittent drying is recognized as one of the most effective methods to achieve that objective. Many theoretical and experimental investigations have been done to improve different quality attributes by applying intermittent drying [11]

I.12.1 Nutritional quality

Nutritional quality is defined as the value of the product for the consumer's physical health, growth, development, reproduction and psychological or emotional well-being. This extended definition of nutritional quality can be divided into two terms. One term is for the effects of food determined by its substance, i.e., the sum of all ingredients, beneficial and harmful compounds and their nutritional (or biological) aspects.

As a function of inherent inconsistencies ranging from soil and climate differences to effects of cultivars, seasons and agricultural practices, differences in desirable ingredients are less pronounced compared with undesirable ingredients. Where differences are detected, the higher product quality is mostly found in organic produce. A potential advantage of organic agriculture in producing healthy foods is based on higher concentrations of beneficial secondary plant substances in organically grown crops compared to nonorganically grown crops. [17].

I.12.2 Color quality

Color is an important aspect in the purchasing decision of consumers when it comes to dried food products. The color of dried foods is influenced by structural and biochemical changes during drying, which occur throughout the process. Studies have shown that intermittent drying with an appropriate temperature pattern can significantly reduce color degradation, as it allows for the formation of a protective moisture layer and reduces oxidative reactions. Intermittent LPSSD was found to minimize color degradation as compared to vacuum drying, and longer drying periods can introduce extra residual oxygen, affecting the color of the product. Furthermore, intermittent convective-assisted microwave drying has been found to produce better sensorial quality, such as color and texture.

The main factors affecting color changes are the degradation of pigments, enzymatic and non-enzymatic browning, and the roughness of the product, hue angle is used to characterize colour in food products and represents the purity of brown colour,, which is an important parameter in drying processes where enzymatic and non-enzymatic browning takes place. The total colour change (ΔE) (EqI.2) is used to describe the colour change during drying: [18],[11]

Total color changes (ΔE) can be measured by the following equation:

$$\Delta E = \text{racine carrée} \left(\Delta L^2 + \Delta a^2 + \Delta b^2 \right) \qquad \text{Eq (I.2)}$$

where L represents lightness, a represents redness or greenness
while b represents blueness or yellowness values and D represents
changes in each value.

I.12.3 Physical quality

One of the primary physical changes that occur during intermittent drying is the reduction in moisture content, which can affect the texture, flavor, and nutritional quality of the food product. As the moisture is removed, the food product may become harder, tougher, and more brittle, which can affect its overall sensory quality.

Another physical change that can occur during intermittent drying is shrinkage, where the food product reduces in size due to the loss of moisture. This can affect the appearance and texture of the food product, and in some cases, it may result in cracking or deformation of the product.

I.13 Effect of Intermittent drying on energy consumption

Drying technologies require a lot of energy, accounting for up to 15% of industrial energy usage, with low thermal efficiency. Researchers use techniques such as integrating drying technology with heat pump systems, utilizing waste heat for drying, and intermittent drying to reduce energy usage. Intermittent drying decreases effective drying time and utilization of drying air, reducing energy requirements. Studies show that on/off intermittent drying is the most effective method for reducing energy consumption. The temperature of materials during drying can be measured or estimated mathematically. Mathematical modeling is preferred for rapid estimation in complex dryer designs. [33]

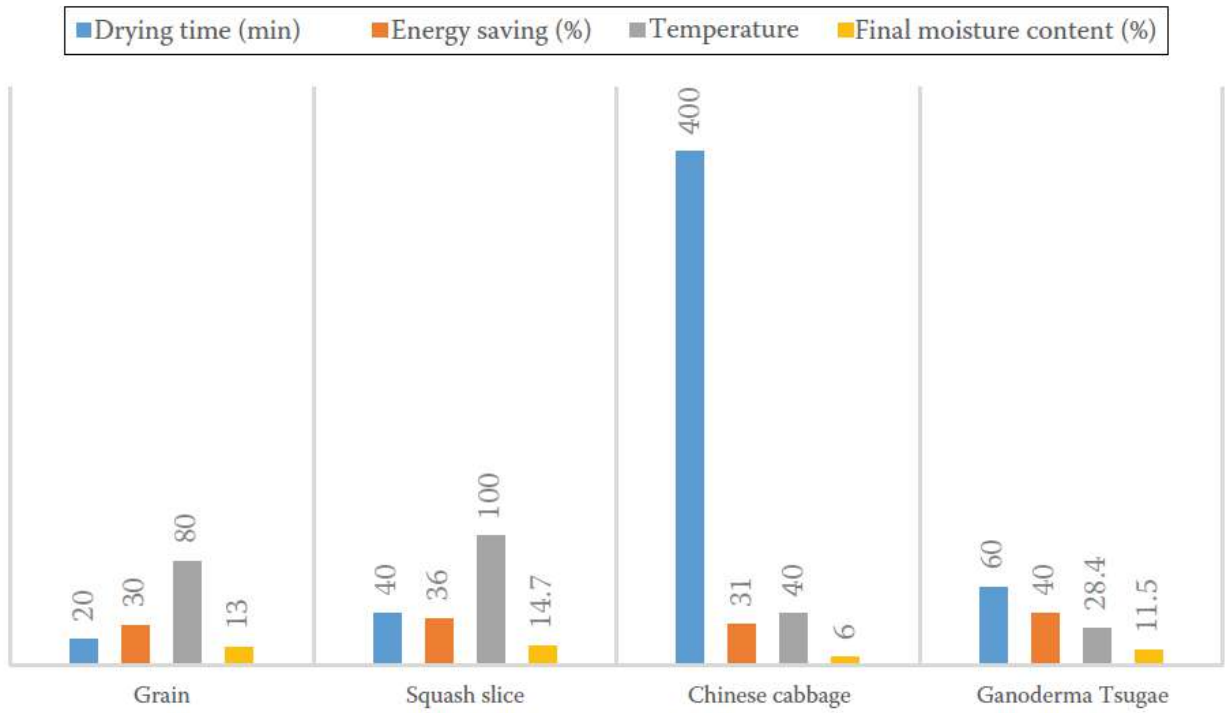

Fig I.7. Effect of on/off intermittent drying mode on energy for different products.[33]

I.14 Modelling of intermittent drying

Modelling is necessary for evaluating the effect of process parameters and optimizing drying process. The dehydration of foodstuffs is a very complex process because of its complexity in internal structure and behavior during drying. Complexity further increases if any form of intermittency is introduced. Therefore, it is very difficult to represent the exact conditions mathematically during drying. Some assumptions are obvious to develop mathematical models. Developing a reasonably good drying model for agricultural products is a challenging task. Although modelling with time varying drying air condition is challenging, several drying models have been proposed to describe the intermittent drying [19]

These models can be categories as empirical and fundamental models

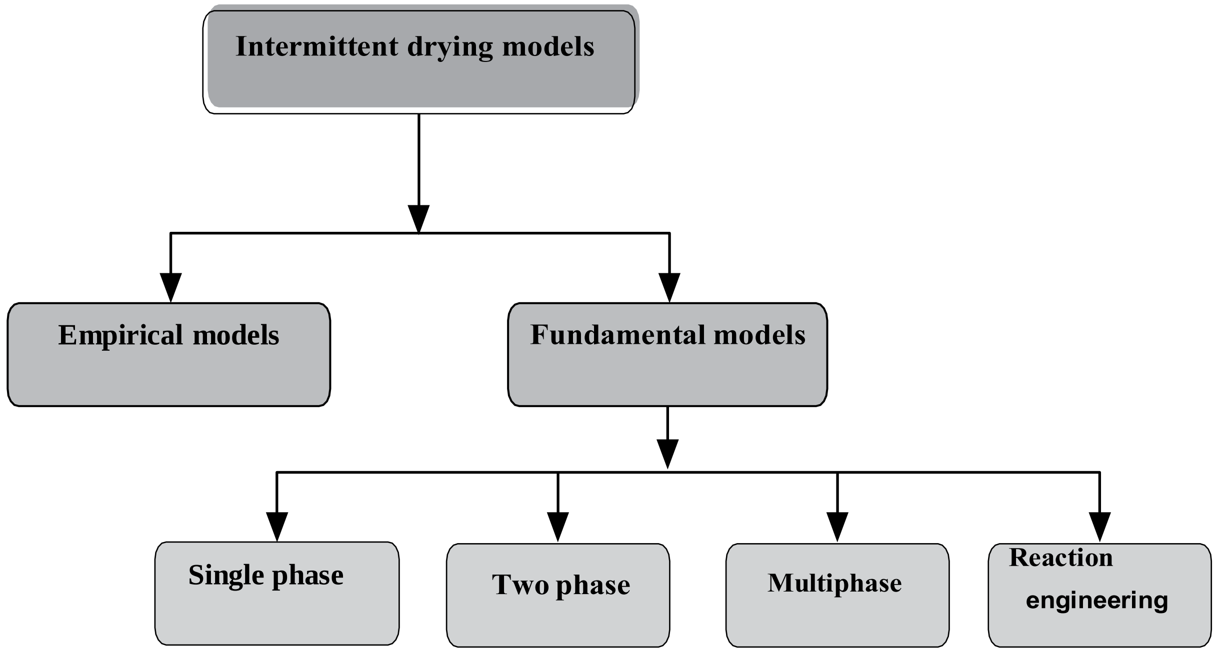

Fig I.8. Modelling approach of intermittent drying. [34]

I.14.1 Empirical models

Empirical models are frequently used to describe the drying curve as they are easy to apply. These models are based on Newton's law of cooling and Fick's law of diffusions. There are several empirical models available for describing drying kinetics. The Page model, which was proposed in 1949, is the most commonly used. It can be described by the equation shown in Eq. (3)

$$\mathbf{MR= exp\ (-kt^n)} \qquad \textbf{Eq}\ (I.3)$$

Where:

MR is the moisture ratio defined as $MR = \frac{Mt-Me}{M0-Me}$, and Mt is the moisture content at time t, Me is equilibrium moisture content and M0 is initial moisture content and n is model constants (dimension-less) and k is the drying constants (s^{-1}) [19].

I.14.2 Fundamental models

Using fundamental mathematical modeling is useful for various applications and optimization. However, developing a fundamental intermittent drying model can be challenging since the required parameters are distinct from those used in continuous drying. Nonetheless, several researchers have developed intermittent drying models based on certain assumptions. To better understand these models, the discussion on fundamental mathematical models for intermittent drying is divided into four parts: (1) Multiphase (2) Reaction engineering (3) a single-phase model that focuses on moisture and (2) a double-phase model that considers both moisture [19].

Chapter II:
Literature review

II .1 Introduction

In this section, we summarized some previous experiments that investigated the influence of intermittent hot air drying on the energy consumption and quality of the tested samples. Various methods were applied, including on-off cycles and temperature variations. The main focus was to assess the effects of intermittent drying on energy consumption and quality characteristics.

II.2. Tempering period (on/off)

Renjie Dong et al.2008 [20]

The researchers conducted a study to understand the moisture distribution in rice kernels during the tempering drying process. They performed intermittent drying of two types of rough rice (long-grain and short-grain) and estimated the moisture content distribution within the kernels using a simplified sphere drying model. The accuracy of the model in simulating the drying and tempering processes was assessed.

The study found that moisture content gradients were created during the drying periods, which decreased significantly during the early stage of the tempering (every hour of drying is followed by an hour of rest) process and then gradually decreased. Temperatures of 50°C for 120 minutes were found to remove about 80% of the moisture content gradients created during drying.

Siew Kian Chin et al , 2010 [21]

In this study the researchers found that intermittent heat pump drying of Ganoderma tsugae reduced the effective drying time compared to continuous heat pump drying. However, as the intermittency decreased from 0.67 to 0.2, the lower water-soluble polysaccharides content was retained.

Santiago A et al, 2012 [22]

The study aimed to evaluate the reduction of energy consumption during the drying of yerba maté branches by applying tempering periods. An empirical model was developed and validated to describe the moisture variation with time and process temperature under different operating conditions. The model was used to simulate an industrial dryer to minimize energy consumption while maintaining a constant final moisture content. The best results were achieved by applying heat for 15 minutes, followed by a 15-minute tempering period, and then continuous heat application. The bed height was reduced by 10% while increasing the belt velocity to maintain the dryer production. These conditions led to a 10% reduction in energy consumption.

Szadzińska, J,2014 [23]

The researchers conducted experiments to investigate the influence of convective-intermittent drying on the kinetics, energy consumption, and quality of green pepper. They conducted hot air drying tests at two different constant air temperatures of 70◦C and 50◦C, and they found that exposure to increased air temperature shortened the overall drying time by about 1 hour, but negatively affected the important quality characteristics of green pepper such as color and nutrient content. Therefore, they tried to find a drying mode that improves the quality of dried biomaterial and also the drying kinetics. They investigated the drying tests in intermittent conditions. The purpose of intermittency was to level moisture distribution in dried products during tempering periods, and thus, to improve the efficiency of the drying process and the product quality.

They tested two modes of stepwise air temperature changing, namely, with 5 min heating and 30 min cooling cycles (mode 5 on – 30 off), and also with 10 min heating and 30 min cooling (mode 10 on – 30 off). During intermittent drying, the air temperature ranged between 56 – 72◦C, and between 45 – 54◦C on average for drying tests carried out at 70◦C and 50◦C, respectively. The dried green pepper samples achieved the final moisture content after about 134 min and 196 min. The researchers found that periodical changes of air temperature provided a rather safe drying temperature, especially for the intermittent drying test carried out at 50◦C. Both, a higher number of cooling cycles and lower air temperature caused the lengthening of the total drying time by about 1 hour. However, it protected against excessive overheating and retained the quality of the dried biomaterial.

- **Continuous drying period**

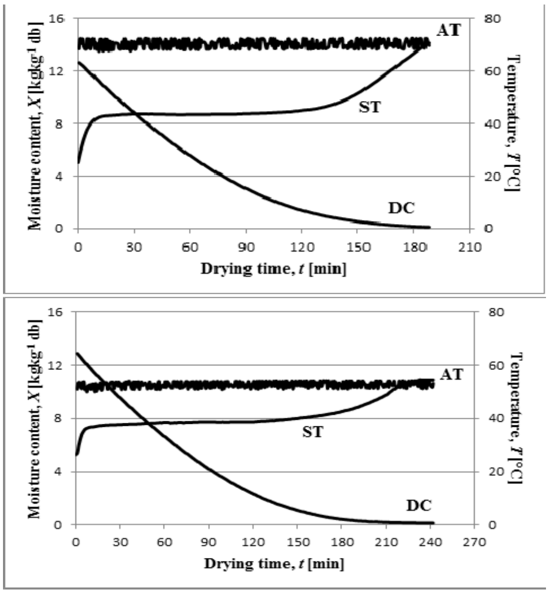

Fig II.1. Colorimetric data of green pepper samples (st., it. stationary, intermittent conditions).

-Intermittent drying period

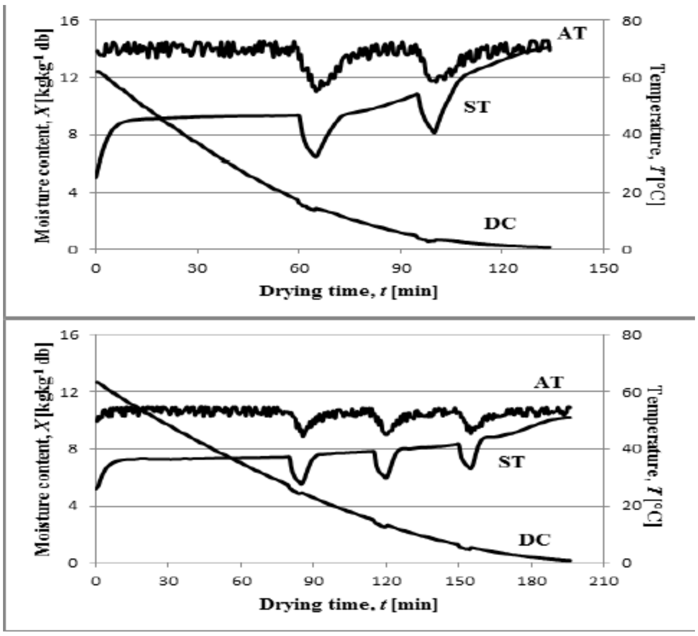

Fig II.2 The drying curves and the temperature profiles **[23].**

Ali Ghasemi et al , 2017 [24]

In this study, the researchers investigated multi-stage intermittent drying (MSID) of rough rice using stress cracking index (SCI), tempering index (TI), and total drying/tempering duration for Hashemi and Koohsar varieties. They conducted experiments where the samples were dried at 60 °C for 20, 40, and 60 minutes, and tempered at 60 °C for 40, 80, 120, 160, 200, and 240 minutes after each drying stage. They assessed the completion of the tempering process using the TI, and analyzed the moisture content kinetics using a simplified drying model.

The researchers found that the SCI decreased significantly until continuing the tempering operation to certain durations, and increased for longer drying durations in each drying stage. Based on the SCI and the total drying/tempering duration, they determined the tempering durations of 200 and 160 minutes after 40 minutes drying in each stage as the best carried out conditions for MSID of Hashemi and Koohsar varieties, respectively.

The results achieved by the TI were in conformity with those obtained by the mathematical model. The researchers concluded that the TI and simulation of surface moisture content on a kernel could be used to estimate the time required for supplementation of the tempering process to eliminate moisture content gradients created inside the kernels during the drying process.

Wafa Hajji et al, 2020 [25]

They have developed a new drying technique called Interval Starting Accessibility Drying (ISAD) to address the issue of high energy consumption in conventional drying methods. The ISAD method involves exposing food samples to a short burst of hot air near the beginning of the drying process, followed by brief tempering periods. Quince samples were subjected to ISAD at a temperature of 40°C and varying air flow velocities (2, 3.5, and 5 m/s), with 15 seconds of active drying time and tempering periods ranging from 1 to 5 minutes.

The researchers compared the effectiveness of ISAD to conventional drying methods in terms of drying time and energy consumption. They found that ISAD significantly reduced the effective drying time by approximately 89% compared to conventionally dried quince samples, while still achieving the same final water content. This reduction in drying time resulted in a significant energy savings.

Overall, the study demonstrated that ISAD is a promising technique for improving the efficiency of fruit drying processes, and has potential for wider application in the food industry.

Fig II.3. Laboratory-scale convective air dryer of INAT **[25]**

R. Md Saleh et al, 2020 [26]

The objective of this research was to investigate the effect of intermittent drying on the drying kinetics, moisture diffusivity, and quality of organic carrot. The researchers conducted intermittent drying at 60°C and 70°C with a constant air velocity of 0.6 m/s. The drying process was paused at 30% and 40% moisture levels to investigate the retention of total carotenoids and other quality parameters.

The results showed that tempering, which is the process of holding the partially dried product at a specific moisture content, had a significant effect on the specific energy consumption of the drying process. Temperatures of 60°C and tempering at a moisture level of 30% resulted in the best retention of total carotenoids, total color change, and rehydration ratio. The effective drying time was also shorter at this condition compared to tempering at 40% moisture level.

Moisture diffusivity increased when drying was conducted at 70°C compared to 60°C for both moisture levels and tempering periods. The researchers found that the ideal drying condition was at 60°C with a tempering time of 3 hours at 30% moisture level (wb), which resulted in the best retention of total carotenoids (76.9% ± 2.42), total color change (8.1 ± 1.67), and rehydration ratio (0.4 ± 0.01).

Overall, the study provides valuable insights into the effect of intermittent drying on the drying kinetics and quality of organic carrot. The results suggest that the use of intermittent drying with tempering can help to improve the retention of important quality parameters and reduce specific energy consumption during the drying process.

Mojtaba Nosrat et al, 2021 [27]

The researchers conducted an experimental and numerical study to analyze the moisture variation and fissure formation of rough rice kernels during multi-stage intermittent drying (MSID) in a laboratory-scale infrared-assisted vibratory bed dryer. They varied the drying parameters including far-infrared radiation (FIR) intensity, inlet drying air temperature, drying duration, and tempering ratio. They also predicted the two-dimensional moisture distribution within individual kernels, determined the drying rate, percentage of cracked kernels (PCK), and specific energy consumption (SEC) experimentally, and simulated the results.

Based on their analysis, they found that the magnitude of 10% d.b. mm^-1 was considered as an index for the critical value for moisture content gradient (MCG) to achieve suitable drying and tempering duration. They recommended that the intermittent drying duration at each stage should be selected in such a way that the MCG value does not exceed the critical level, and the shortest possible tempering duration should be chosen in a manner that at least 40% of the critical level of MCG is eliminated. They also identified the suitable treatment for intermittent drying, which was at FIR intensity of 1000 W m^-2, inlet air temperature at 40 C, drying duration at 30 min, and tempering ratio at 4.

Akhilesh Singh et al,2022 [28]

In this study, a solar-assisted heat pump dryer was developed and used to investigate the effects of different intermittency ratios on energetic, exergetic, and economic performances during the drying of radish chips. The experiment was conducted using future refrigerant, R1234yf. The drying process was performed intermittently, and the total drying time (on-period + off-period) was varied to assess its impact on the drying efficiency (DE), energy efficiency, moisture extraction rate (MER), and specific moisture extraction rate (SMER). The results showed that the intermittent drying process resulted in higher values of MER and SMER compared to continuous drying, and these values increased with decreasing intermittency ratio. The economic analysis revealed that a lower intermittency ratio led to a shorter payback period, and intermittent drying was found to be much better than continuous drying in terms of enhancing the specific moisture extraction rate and energy efficiency while reducing drying costs. The study concludes that intermittent drying with a solar-assisted heat pump dryer is a promising approach for the efficient drying of food chips.

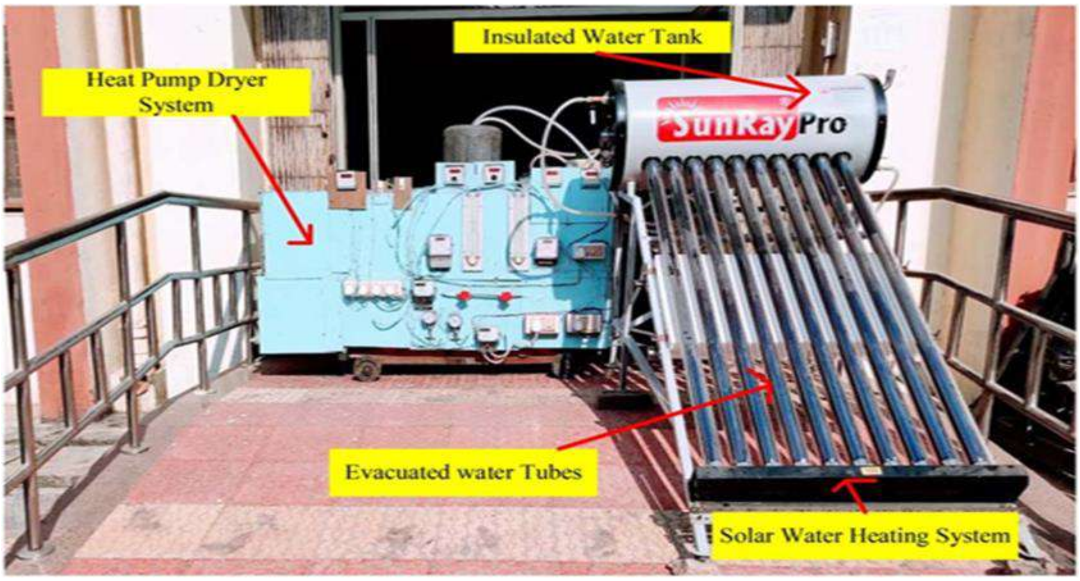

Fig II.4.Developed experimental facility of SAHPD for intermittent drying **[28]**

II.3 Temperature variation applications

Chien Hwa Chong et al, 2011 [29]

In this study, the researchers investigated the application of intermittent drying using cyclic temperature and step-up temperature in enhancing the textural attributes of dehydrated Manilkara zapota (a type of fruit). They used hot air and dehumidified air alternately in the drying process to reduce the hardness and chewiness of the dried samples,The researchers identified the critical moisture content that contributed to case hardening effects at different drying profiles, which was found to be 0.15 gH2O=gDM. They also determined that the most suitable drying profile for Manilkara zapota was 5C-19H,In terms of drying performance, the researchers found that intermittent drying using dehumidified air drying followed by hot air drying or vice versa was effective in reducing the moisture content to a desirable final moisture content in a short drying duration. They concluded that intermittent drying with dehumidified air tempering can be applied in industrial drying of agricultural products as one of the techniques for producing a desirable dehydrated product quality in terms of texture attributes.

Table 1: Definition of Intermittent drying profiles

Code=notation	First period	Second period	Third period
5H-1C-18H	5 h of hot air drying	1 h of cold air drying	18 h of hot air drying
4H-2C-18H	4 h of hot air drying	2 h of cold air drying	18 h of hot air drying
3H-3C-18H	3 h of hot air drying	3 h of cold air drying	18 h of hot air drying
2H-4C-18H	2 h of hot air drying	4 h of cold air drying	18 h of hot air drying
2C-22H	2 h of cold air drying	22 h of hot air drying	
3C-21H	3 h of cold air drying	21 h of hot air drying	
4C-20H	4 h of cold air drying	20 h of hot air drying	
5C-19H	5 h of cold air drying	19 h of hot air drying	

Essohouna Takougnadi et al, 2017 [30]

In this study, the researchers aimed to develop an intermittent energy-saving drying process for onion slices that would preserve the quality attributes of the onion. They conducted experiments using different drying conditions, such as temperature and air flow rates, and determined the critical drying times for each condition. They found that the most energy-efficient couple was 65°C temperature and 24 dm3/s air flow rate.

Next, the researchers developed an intermittent drying process (step-down) using the critical drying times and the most energy-efficient couple. They compared this step-down process with the most energy-saving continuous drying process at 65°C and 24 dm3/s air flow rate. The results showed that the intermittent process was 12.70% more energy-efficient than the continuous process and maintained the nutritional quality of the onion, specifically fat content, vitamin C, and proteins.

Finally, the researchers modeled the drying kinetics using ten empirical models and found that the two-term exponential model and the Midilli model described both the continuous drying and the developed intermittent process. Overall, the study demonstrated the feasibility of an intermittent drying process for onion slices that could save energy and maintain nutritional quality.

[Đorđije Doder et al, 2022] [31]

The study investigated the application of intermittent regimes for batch drying of wheat grains. The effects of intermittency on moisture content, drying air oscillation, and moisture removal rate were analyzed. The results showed that intermittency had a significant influence on the first 300 minutes of drying time, with higher layers showing no significant temperature or drying rate oscillations but were simply dried slower. Only layers up to 15 cm high achieved the desired final moisture content of 16% dry basis. The study suggested that energy savings and drying time reduction could be achieved for lower layers and the initial 300 minutes of drying time. However, total drying time might not be affected due to the low effective diffusivity of the wheat grains. The study proposed conducting intermittent drying with shorter periods for higher layers and recommended further investigation into other intermittent regimes and temperatures for wheat processing.

II.4 tempering period coupled with a temperature variation

Morteza Golmohammadia et al, 2014 [32]

This study focused on investigating the energy consumption of intermittent drying of paddy rice. A mathematical model consisting of two parts was developed to describe the moisture distribution within a grain for both drying and tempering stages. The model was based on Fick's second law of diffusion within a sphere and was solved analytically. The effects of different parameters, namely air temperature and velocity, were experimentally investigated using a lab-scale fluidized bed dryer. Moisture diffusivity was estimated in Arrhenius form using experimental results.

Initially, 1 kg of sample was dried using hot air at specified temperatures (40, 50, 60◦C) and humidity in a one-hour period then, the fluidized bed content was put into rest for a periodof 3 h. After tempering stage, the sample was dried again for30 min.

The researchers then utilized the model in an optimization problem to minimize the total energy consumption. Based on the experimental results, it was found that the impact of air velocity on drying characteristics was negligible. The optimization results showed that employing the tempering stages substantially reduced the energy consumption. The tempering process also dictated a process that begins with longer drying stages and lower temperatures, while the subsequent stages were shorter with higher temperatures. Overall, the study aimed to investigate the energy efficiency of intermittent drying of paddy rice and suggest optimization strategies for reducing energy consumption

From these studies, it can be concluded that intermittent drying techniques have shown promising results in terms of improving the efficiency of the drying process, reducing energy consumption, and improving the quality of dried food products. Using intermittent drying with tempering periods can help distribute moisture, protect against excessive temperature rise, and retain important quality characteristics such as color, nutrient content, and texture. Various methods of intermittent drying, including on and off cycles, temperature variations, and multistage drying, have been explored and found to be effective in decreasing drying time, increasing moisture extraction rates, and improving energy efficiency.

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ملخص

هذه مذكرة ماستر تقدم نتائج دراسة أجريت في مختبر URAER في غرداية، تركز على تجفيف التمور المعاد ترطيبها باستخدام تقنية التجفيف المتقطعة. هدف البحث هو تقييم تأثير التجفيف المتقطع على استهلاك الطاقة وجودة المنتج مقارنةً بطرق التجفيف المستمرة التقليدية، وتحسين جودة التمور الجافة بشكل زائد وتحديد أفضل النماذج التجريبية لهذه الدراسة. شمل التصميم التجريبي 18 تجربة، حيث خضعت التمور المجففة بشكل زائد والصلبة لمعاملتين: إعادة الترطيب حتى انقلاب السكر والنضج المكمل، وكان التركيز الرئيسي على التجفيف المتقطع بالهواء الساخن باستخدام وحدة تكييف هواء معدلة، التي توفر بديلًا لطرق التجفيف المستمر المكثفة للاستهلاك الطاقوي. أظهرت النتائج أن سرعة الهواء لها تأثير ضئيل على وقت التجفيف، ولكن زيادتها تؤدي إلى زيادة استهلاك الطاقة. بالمقابل، إدخال فترات التبريد أثناء التجفيف لا يزيد بشكل كبير من وقت التجفيف ويؤدي إلى توفير طاقة تصل إلى حوالي 40٪. تم استخدام سبعة نماذج رياضية لوصف حركية التجفيف في الطبقة الرقيقة للتمور. أظهرت النتائج أن النموذجين Midilli-Kucuk والنموذج اللوغارتمي هما النماذج الأكثر ملاءمة لوصف عملية التجفيف المتقطعة بالهواء الساخن في النموذج المدروس. تشير النتائج إلى أن التجفيف المتقطع يمكن أن يكون نهجًا مفيدا سواء لاقتصاد الطاقة أو للحفاظ على نوعية التمور المجففة.

Résumé

Ce mémoire de master présente les résultats d'une étude menée au laboratoire de l'URAER à Ghardaïa, portant sur le séchage des dattes réhydratées à l'aide de la technique de séchage intermittent. L'objectif de la recherche est d'évaluer l'impact du séchage intermittent sur la consommation d'énergie et la qualité du produit par rapport aux méthodes traditionnelles de séchage continu, d'adoucir et d'améliorer la qualité des dattes trop sèches et de déterminer le meilleur modèle empirique pour cette étude. La conception expérimentale comprenait 18 essais, où les dattes trop sèches et dures ont subi deux traitements : réhydratation jusqu'à inversion du sucre et maturation complémentaire, et l'accent a été mis sur le séchage intermittent à l'air chaud à l'aide d'une unité de climatisation modifiée, offrant une alternative aux méthodes de séchage continu intensives en consommation énergétique. Les résultats révèlent que la vitesse de l'air n'a qu'un effet minimal sur le temps de séchage, mais son augmentation entraîne une augmentation de la consommation d'énergie. En revanche, l'introduction de périodes de temporisation pendant le processus de séchage n'augmente pas de manière significative le temps de séchage et permet de réaliser des économies d'énergie d'environ 40%. Sept modèles mathématiques ont été utilisés pour décrire la cinétique de séchage en couche mince des dattes. Les résultats ont montré que les modèles Midilli-Kucuk et Algorithmique étaient les modèles les plus appropriés pour décrire le processus de séchage intermittent à l'air chaud dans le prototype examiné. Les résultats suggèrent que le séchage intermittent peut être une approche bénéfique à la fois pour les économies d'énergie et la préservation de la qualité des dattes séchées.